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RECENT RE-MEASUREMENT OF NEUTRON AND GAMMA-RAY SPECTRA 1080 METERS FROM THE APRD CRITICAL FACILITY

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F. A. Robitaille and B.E. Hoffarth

DEFENCE RESEARCH ESTABLISHMENT OTTAWA
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ABSTRACT

Previously reported measurements of long-range air-transported neutron and gamma-ray spectra from the fast-critical facility at the US Army Aberdeen Proving Ground have been supplemented recently at the 1080-meter position. The results of these determinations are presented herein and compared to several recent calculations from other research establishments.

In addition, a summary of all dosimetric measurements obtained in the period 1979-1982 are appended, as are new determinations of APRD soil composition.

Integral quantities such as neutron and gamma-ray kermas are very well predicted by the latest calculations, however there still exist significant spectral differences. At short ranges calculated neutron spectra are somewhat softer than experimental measurements, but at the farthest range of 1080 meters agreement is surprisingly good. Gamma-ray spectra remain well-calculated at all ranges.

RÉSUMÉ

On présente ici le complément, à l'altitude de 1080 mètres, des mesures déjà citées et faites lors de vols de longue portée, par les installations expérimentales de la base militaire américaine d'Aberdeen, concernant les spectres d'émissions neutroniques et de rayons gamma. On a comparé les résultats de ces mesures à plusieurs calculs récents effectués par d'autres centres de recherches.

En outre, dans la section annexe figure un résumé de toutes les mesures dosimétriques, de même que de nouvelles analyses de la composition des sols de l'APRD.

Les calculs les plus récents permettent très bien d'évaluer des quantités intégrales telles que les kermas engendrés par les neutrons et les rayons gamma; on observe toutefois d'importantes différences spectrales. A faible altitude, les spectres neutroniques son légèrement moins prononcés que dans les mesures expérimentales, mais à l'altitude plus grande de 1080 m, la concordance est étonnamment bonne. Les spectres gamma restent correctement calculés à toutes les altitudes.

TABLE OF CONTENTS

PAGE

ABSTRACT iii

TABLE OF CONTENTS iv

LIST OF ILLUSTRATIONS vi

LIST OF TABLES ix

1.0 INTRODUCTION 1

2.0 EXPERIMENT 2

2.1 Geometry 2

2.2 Radiation Source 2

2.3 Detectors 5

2.4 Soil Composition 6

3.0 EXPERIMENTAL RESULTS 6

3.1 Review of 1980 Spectroscopy 6

3.2 1981 Measurement at 1080 Meters 10

3.3 Bonner-Sphere Determinations 12

3.4 High Temperature and Humidity Measurements 13

3.5 Integral Dosimetry 13

3.6 Discussion 20

4.0 THEORETICAL CALCULATIONS 21

4.1 Previous ORNL and DREO Calculations 21

4.2 Recent LANL, SAI and LLNL Calculations 21

TABLE OF CONTENTS - (Continued)

PAGE

4.3 Comparison to Experimental Spectroscopy 22

4.4 Comparison to Experimental Dosimetry 29

4.5 Discussion 29

5.0 CONCLUSIONS 31

6.0 ACKNOWLEDGEMENTS 32

7.0 REFERENCES 33

8.0 APPENDICES 37

A. Plotted DREO Free-Field Neutron Spectra 37

B. Plotted DREO Free-Field Gamma-Ray Spectra 49

C. Listed Fine Group DREO Neutron Spectra 61

D. Listed Fine Group DREO Gamma-Ray Spectra 69

E. DREO Neutron Spectra in 37-Group Format 77

F. DREO Gamma-Ray Spectra in 21-Group Format 83

G. Summary of Free-Field Integral Measurements 89

H. Theoretically-Calculated Integral Quantities 99

I. APRD Soil Composition 103

J. Neutron and Gamma-Ray Spectra from Californium-252 109

LIST OF ILLUSTRATIONS

PAGE

Figure 1. APRD Site and Detector Locations 3

Figure 2. Measured Neutron Spectra at a Ground Range of 100 Meters 7

Figure 3. Measured Neutron Spectra at a Ground Range of 170 Meters 7

Figure 4. Measured Neutron Spectra at a Ground Range of 300 Meters 8

Figure 5. Measured Gamma-Ray Spectra at a Ground Range of 100 Meters 8

Figure 6. Measured Gamma-Ray Spectra at a Ground Range of 170 Meters 9

Figure 7. Measured Gamma-Ray Spectra at a Ground Range of 300 Meters 9

Figure 8. Neutron Spectra Measured in 1980 and 1981 at 1080 Meters 11

Figure 9. Gamma-Ray Spectra Measured in 1980 and 1981 at 1080 Meters 11

Figure 10. Neutron Spectrum Measured in 1982 at 1080 Meters 14

Figure 11. Gamma-Ray Spectrum Measured in 1982 at 1080 Meters 14

Figure 12. Measured Neutron Fluence Above 3 MeV 15

Figure 13. Measured Neutron Tissue-Kerma 16

Figure 14. Measured Gamma-Ray Tissue-Kerma 17

Figure 15. Measured Total Tissue-Kerma 18

Figure 16. LANL vs DREO Neutron Spectra at 170 Meters 23

Figure 17. LANL vs DREO Neutron Spectra at 400 Meters 24

Figure 18. LANL vs DREO Neutron Spectra at 1080 Meters 25

Figure 19. SAI vs DREO Neutron Spectra at 170 Meters 26

LIST OF ILLUSTRATIONS - (Continued)

PAGE

Figure 20. SAI vs DREO Neutron Spectra at 400 Meters..... 26

Figure 21. SAI vs DREO Neutron Spectra at 1080 Meters..... 27

Figure 22. SAI vs DREO Gamma-Ray Spectra at 170 Meters..... 27

Figure 23. SAI vs DREO Gamma-Ray Spectra at 400 Meters..... 28

Figure 24. SAI vs DREO Gamma-Ray Spectra at 1080 Meters..... 28

Figure 25. Comparison of Theoretical and Experimental Integral Quantities..... 30

Figure A-1. Free-Field Neutron Spectrum at 15 Meters (1980) 39

Figure A-2. Free-Field Neutron Spectrum at 100 Meters (1980) 40

Figure A-3. Free-Field Neutron Spectrum at 170 Meters (1980) 41

Figure A-4. Free-Field Neutron Spectrum at 179 Meters (1981) 42

Figure A-5. Free-Field Neutron Spectrum at 260 Meters (1981) 43

Figure A-6. Free-Field Neutron Spectrum at 300 Meters (1980) 44

Figure A-7. Free-Field Neutron Spectrum at 400 Meters (1980) 45

Figure A-8. Free-Field Neutron Spectrum at 1080 Meters (1980) 46

Figure A-9. Free-Field Neutron Spectrum at 1080 Meters (1981) 47

Figure A-10. Free-Field Neutron Spectrum at 1080 Meters, Under Conditions of High Temperature and Relative Humidity (1982) 48

Figure B-2. Free-Field Gamma-Ray Spectrum at 100 Meters (1980) 51

Figure B-3. Free-Field Gamma-Ray Spectrum at 170 Meters (1980) 52

Figure B-4. Free-Field Gamma-Ray Spectrum at 179 Meters (1981) 53

Figure B-5. Free-Field Gamma-Ray Spectrum at 260 Meters (1981) 54

Figure B-6. Free-Field Gamma-Ray Spectrum at 300 Meters (1980) 55

Figure B-7. Free-Field Gamma-Ray Spectrum at 400 Meters (1980) 56

LIST OF ILLUSTRATIONS - (Continued)

PAGE

Figure B-8. Free-Field Gamma-Ray Spectrum at 1080 Meters (1980) 57

Figure B-9. Free-Field Gamma-Ray Spectrum at 1080 Meters (1981) 58

Figure B-10. Free-Field Gamma-Ray Spectrum at 1080 Meters, Under Conditions of High Temperature and Relative Humidity (1982) 59

Figure J-1. Neutron Spectrum Recorded by DREO One Meter from the APRD Cf^{252} Source 111

Figure J-2. Gamma-Ray Spectrum Recorded by DREO One Meter from the APRD Cf^{252} Source 112

Figure J-3. Cf^{252} Neutron Spectrum Recorded by DREO in 1978 114

Figure J-4. Comparison of DREO Measurement to SRL Calibration of the Neutron Emission Rate (> 600 KeV) from a Californium-252 Source 115

LIST OF TABLES

PAGE

TABLE 1. Bonner-Sphere Counting-Rate Ratios 12

TABLE 2. Atmospheric Parameters During Measurements at 1080 Meters . 13

TABLE C-1. Neutron Spectrum at 15m (1980) 64

TABLE C-2. Neutron Spectrum at 100m (1980) 64

TABLE C-3. Neutron Spectrum at 170m (1980) 65

TABLE C-4. Neutron Spectrum at 179m (1981) 65

TABLE C-5. Neutron Spectrum at 260m (1981) 66

TABLE C-6. Neutron Spectrum at 300m (1980) 66

TABLE C-7. Neutron Spectrum at 400m (1980) 67

TABLE C-8. Neutron Spectrum at 1080m (1980) 67

TABLE C-9. Neutron Spectrum at 1080m (1981) 68

TABLE C-10. Neutron Spectrum at 1080m (1982) 68

TABLE D-2. Gamma-Ray Spectrum at 100m (1980) 71

TABLE D-3. Gamma-Ray Spectrum at 170m (1980) 71

TABLE D-4. Gamma-Ray Spectrum at 179m (1981) 72

TABLE D-5. Gamma-Ray Spectrum at 260m (1981) 72

TABLE D-6. Gamma-Ray Spectrum at 300m (1980) 73

TABLE D-7. Gamma-Ray Spectrum at 400m (1981) 73

TABLE D-8. Gamma-Ray Spectrum at 1080m (1980) 74

TABLE D-9. Gamma-Ray Spectrum at 1080m (1981) 74

TABLE D-10. Gamma-Ray Spectrum at 1080m (1982) 75

TABLE E-1. Neutron Spectrum at 15m (1980) 79

TABLE E-2. Neutron Spectrum at 100m (1980) 79

LIST OF TABLES - (Continued)

PAGE

TABLE E-3. Neutron Spectrum at 170m (1980) 79

TABLE E-4. Neutron Spectrum at 179m (1981) 80

TABLE E-5. Neutron Spectrum at 260m (1981) 80

TABLE E-6. Neutron Spectrum at 300m (1980) 80

TABLE E-7. Neutron Spectrum at 400m (1980) 81

TABLE E-8. Neutron Spectrum at 1080m (1980) 81

TABLE E-9. Neutron Spectrum at 1080m (1981) 81

TABLE E-10. Neutron Spectrum at 1080m (1982) 82

TABLE F-2. Gamma-Ray Spectrum at 100m (1980) 85

TABLE F-3. Gamma-Ray Spectrum at 170m (1980) 85

TABLE F-4. Gamma-Ray Spectrum at 179m (1981) 85

TABLE F-5. Gamma-Ray Spectrum at 260m (1981) 85

TABLE F-6. Gamma-Ray Spectrum at 300m (1980) 86

TABLE F-7. Gamma-Ray Spectrum at 400m (1980) 86

TABLE F-8. Gamma-Ray Spectrum at 1080m (1980) 86

TABLE F-9. Gamma-Ray Spectrum at 1080m (1981) 86

TABLE F-10. Gamma-Ray Spectrum at 1080m (1982) 87

TABLE G-1. Integral Quantities Determined Experimentally at APRF 92

TABLE G-2. Average Integral Data Obtained Experimentally 98

TABLE H-1. Calculated Integral Data Interpolated at Experimental Points 101

TABLE H-2. Ratios of Calculated to Average Experimental Data 102

TABLE I-1. Results of Elemental Analysis of DREO Soil Sampling at APRF 106

TABLE I-2 Absolute Elemental Concentrations of APRF Soil (atoms/barn-cm) 107

1.0 INTRODUCTION

In 1978 measurements of the outdoor, free-field radiation environments surrounding the fast-critical facility operated by the U.S. Army Pulse Radiation Division (APRD) at the Aberdeen Proving Ground (Maryland, USA) were made by both APRD [1] and a German group, Wehrwissenschaftliche Dienststelle der Bundeswehr für ABC-Schutz (WWD) [2]. Neutron spectra were measured by both groups using NE-213 proton-recoil spectrometers at ranges of 100 m, 170 m and 300 m. Gamma-ray spectra were measured by WWD at the same ranges, also using an NE-213 scintillator. In addition, integral dosimetric measurements were performed by both groups, using a variety of tissue-equivalent ion-chambers, Geiger-Müller counters and sulphur activation (n,p).

In 1980 measurements of neutron and gamma-ray spectra at these same ranges were performed by personnel from the Defence Research Establishment Ottawa (DREO). Additionally, similar measurements were obtained at ranges of 400 m and 1080 m [3-5]. Measurement at the greater distances was made possible by the provision of a self-contained mobile nuclear laboratory, which rendered unnecessary the cabling of detector signals back to the reactor control building.

The measurements so obtained were compared to theoretical calculations performed by ORNL [6] to 500 meters and by DREO [3] to 1600 meters. Both of these calculations were somewhat deficient - in the ORNL case due to the limited ground range and in the DREO case by a coarse spatial and angular mesh and the use of a "dry-air" approximation. Nevertheless, it was thus concluded that the calculations predicted integral kermas (both neutron and gamma-ray) reasonably accurately but in general both neutron and gamma-ray spectra were somewhat softer than observed experimentally. Above an energy of 3 MeV neutron fluence was underpredicted by about 30%, but below 2 MeV overpredicted by some 10 to 40%. Surprisingly, these differences were most pronounced at the intermediate ranges of 300 and 400 meters, and least pronounced at the farthest range of 1080 meters.

Agreement amongst the three experimental groups was shown to be excellent in the case of integral quantities but with some differences apparent in spectroscopy, particularly above 6 MeV and below 1 MeV in the case of gamma-rays and below 2 MeV in the case of neutrons.

In 1981 re-measurement of neutron and gamma-ray spectra at 1080 meters was made by DREO at a similar time of the year and under almost identical weather conditions, to verify the reproducibility of the single 1980 data-point. The following year (1982) measurement was again made by DREO at this position during the summer months, under conditions of significantly higher temperature and atmospheric humidity both to investigate the influence of these parameters on radiation transmission and to provide better comparative data of interest to those involved in the retrospective calculation of dosimetry at Hiroshima and Nagasaki [7].

The 1981 neutron measurements were complemented by new APRD Bonner-sphere determinations, both at 170 meters and coincidentally with DREO at 1080 meters [8]. In 1982 coincidental measurement with DREO was again made at the 1080-meter position [9]. During the same experimental series APRD

ion-chamber and Geiger-Müller dosimetry was performed at 1618 meters [10] and shortly thereafter Bonner-sphere determinations made at this same distance [11].

Three new theoretical calculations of the APRD radiation environments also became available during 1982, determined by groups at Lawrence Livermore National Laboratory (LLNL) [12], Science Applications Incorporated (SAI) [13] and Los Alamos National Laboratory (LANL) [14]. These generally provide much better reproduction of experimental measurement than previous calculations, however spectral discrepancies continue to exist below a neutron energy of 2 MeV.

In this report a description of the recent spectroscopy and dosimetry will be presented, along with a comprehensive compilation of all previous dosimetric measurements and DREO-measured spectra. Improvements in the accuracy of important experimental parameters will be discussed, in particular relating to distance measurement, soil composition, atmospheric characterization and neutron source anisotropy and normalization. Finally the adequacy of the recent theoretical calculations in reproducing experimental measurement will be examined.

2.0 EXPERIMENT

2.1 Geometry

The APRD critical facility normally resides inside a low-mass aluminum weather-protecting silo. For the purpose of free-field measurements the core may be remotely removed from the silo and positioned at a height above ground of fourteen meters [1]. Detectors are normally positioned at any of five reproducible distances: 100, 170, 300, 400 and 1080 meters, established by laser-range finding equipment. (In earlier reports [3-5] the estimate of ground range to the farthest position was quoted as 1100 meters, resulting from less accurate estimation by aerial photography.)

Terrain surrounding the reactor is clear of growth to approximately 200 meters, and then fairly densely forested beyond (Figure 1). Measurements at 300 and 400 meters were made along the centerline of a twenty-meter wide path cleared to a distance of 450 meters into the forested area. At 1080 meters a small hill of approximate height of 15 meters enabled measurements just above the forest cover. In all cases the detectors were maintained at a height of two meters above the air-ground interface.

2.2 Radiation Source

The APRD fast-pulse facility consists of a compact core of enriched-uranium fuel in the form of a right-circular cylinder [15], similar in design to the Health Physics Research Reactor (HPRR) at the Oak Ridge National Laboratory (ORNL). Steady-state operation for extended periods is possible to a maximum power level of six kilowatts (nominal), as monitored by various fission-chambers [16]. Total neutron leakage above an energy of 100 eV, measured using calibrated fission-chambers horizontally at a distance of one meter from the core centre, is equivalent to an isotropic

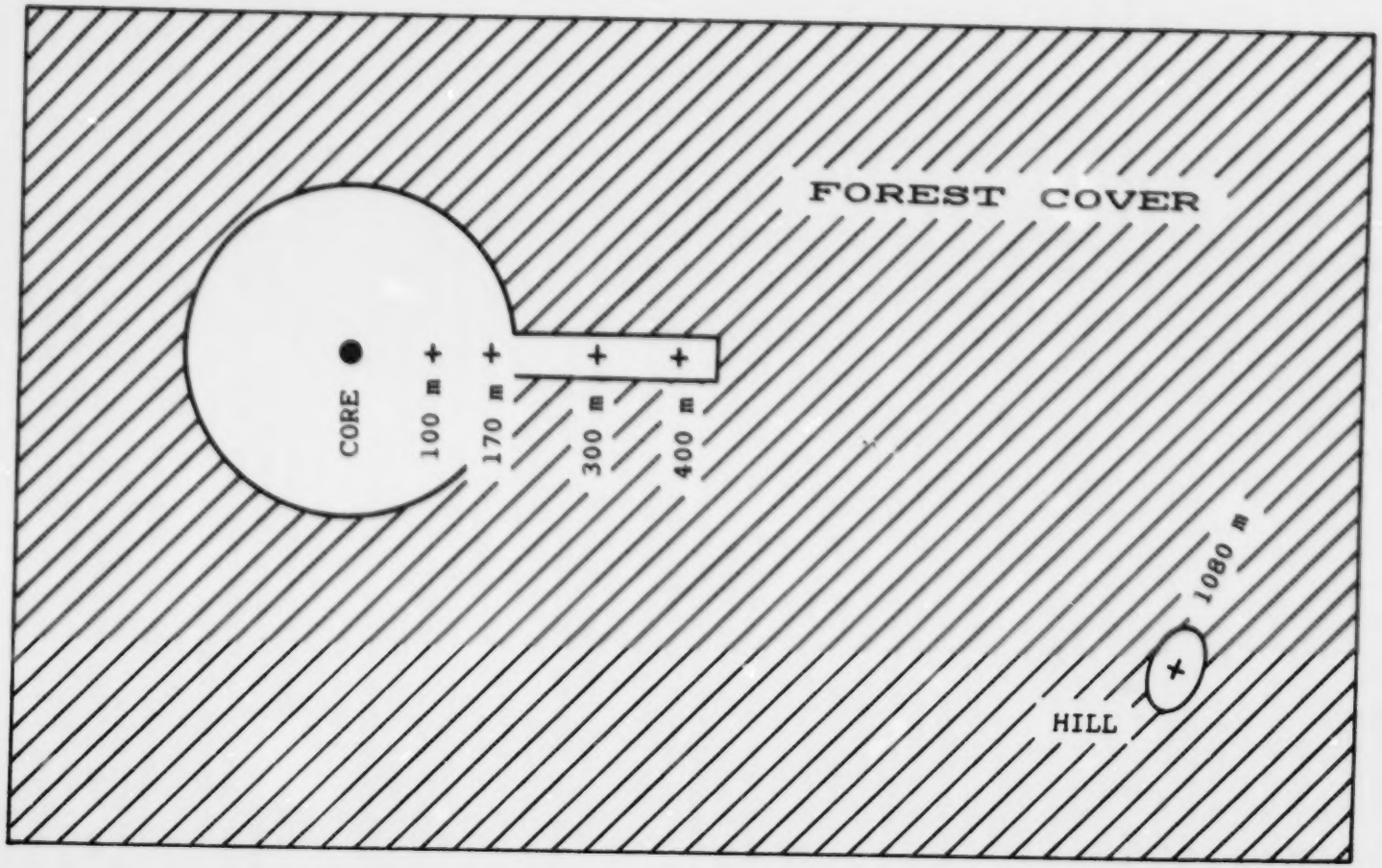

Figure 1 - APRD Site and Detector Locations

source of 1.28×10^{17}(±5%) neutrons per kilowatt-hour [1]. Total gamma-ray leakage at the same point determined by a combination of measurement and calculation is sixty-five percent of the neutron yield [1].

In earlier reports [1-6,8] use of the above neutron-leakage factor was made to normalize measured spectra and doses to "source neutrons" for the purpose of comparison to corresponding air-transport calculation. More recently the angular distribution of fast neutrons one meter from the core centre has been investigated using sulphur-activitation techniques [17] and the resulting spherical-surface integrated total neutron-leakage estimated instead as 1.10×10^{17}(±10%) neutrons per kilowatt-hour. The observed anisotropy of neutron leakage thus complicates comparison to theoretical calculations. Ideally the source term used in air-transport calculations should model exactly the observed anisotropy of neutron production. If an isotropic source term is used instead then the equivalent source yield appropriate for close-in, horizontal measurements would be near 1.28×10^{17} neutrons per kilowatt-hour, whereas for longer-range determinations the equivalent isotropic source would tend more to the value of 1.10×10^{17}, as the effects of source anisotropy are expected to become less significant as source-to-detector separation increases. At intermediate ranges (in which must be included most of the work described herein) it can only be stated with certainty that the apropriate isotropic-equivalent source lies somewhere between these two extremes, which differ by a total of 15%.

Measured results quoted in this report are therefore normalized to "kilowatt-hours" (except where specifically noted otherwise) to facilitate further renormalization as required to either of the above-mentioned leakage factors. Note that "kilowatt-hours" at APRD are not absolutely defined and only represent power levels approximating the thermal release of the core.

Spectral variation of the neutron and gamma-ray source has been calculated on several occasions by ORNL using both one-dimensional (ANISN) and two-dimensional (DOT-3.5) models [1] and more recently at LANL using Monte-Carlo techniques [18] (MCNP). The ORNL core-calculations were previously shown to reproduce spectra consistent with experimental measurements at ten meters using the WWD NE-213 scintillator [1], and APRD proton-recoil and Li^6 detectors at one meter [1]. Such verification may not be definitive, however, due to high dead-time effects, ground-scatter contributions, atmospheric attenuation (approximately one percent per meter at the neutron energies of interest) and very high gamma-ray-to-neutron ratios resulting from fission-product activity. APRD measurements at one meter using less-efficient detectors are less affected by these perturbations, but introduce thc additional possibility of experimental bias since different detectors are employed to measure the air-transported spectra at longer ranges.

In comparison to the ORNL calculation, recent LANL-estimated neutron leakage [18] above 3 MeV is relatively greater by 23%, but below 0.55 MeV lower by 20%. The LANL-calculated fraction of source neutrons above 3 MeV equals 0.145, in better agreement with the observed sulphur-to-total fluence ratio of 0.135 [16], than the ORNL-calculated fraction of 0.118. Thus air-transported neutron spectra calculated using the LANL source term would be expected to be "harder" in energy than comparable spectra determined by the ORNL source and consequently in better agreement with long-range experimental measurements utilizing NE-213 spectroscopy [3]. Neutron

fluence above 3 MeV as determined both by NE-213 spectroscopy and sulphur activation has been traditionally undercalculated in the past when the ORNL source term is employed [3-6]. The extent (20-30%) and direction of these underpredictions (above 3 MeV) are such that they would be essentially resolved by the newer LANL source term. The differences in core calculations are possibly due to the use by LANL of more-recent basic fission-process data [19].

At the present time insufficient experimental data obtained at short ranges are available to support either core calculation in a definitive manner. Further measurements are indicated, preferably using the same spectroscopy systems as used for determinations at greater distances. Such measurements should include shadow-bar background measurements to exclude the ground-return component, and be performed at several source-to-detector separations to establish energy-dependent air transmission losses. As a result of the known anisotropy of particle leakage from the core, measurements should be repeated at a representative number of polar angles to determine the extent of energy-angle coupling. Dead-time losses should be minimized by performing such measurements after a substantial core-cooling period.

2.3 Detectors

Neutron and gamma-ray spectra at APRD have been variously obtained by APRD, WWD and DREO using NE-213 liquid organic scintillators, followed by numerical unfolding of observed recoil-proton and recoil-electron distributions. Both WWD and APRD used a cylindrical scintillator of 2" height and 2" diameter and analysed observed data using the FERDOR code [20]. Neutron unfolding employed Verbinski's response matrix [21], renormalized by up to 26% below 2 MeV in order to better reproduce Californium-252 neutron spectra [22] according to the accepted shape. Gamma-ray unfolding is accomplished by WWD using the response matrix of Lurie, et al [23].

DREO uses a slightly smaller scintillator of 1 3/4" height by 2" diameter (to render more isotropic the response to incident neutrons) and a different unfolding technique [24]. The neutron response data were calculated at DREO [25] specifically for this scintillator using the same code as employed by Verbinski [26]. Gamma-ray response data were adopted from Lurie's calculation [23].

In typical APRD radiation environments NE-213 detectors account for essentially all of the incident gamma-ray kerma since the detection threshold is quite low (300 KeV), however a significant fraction (approximately 35%) of the neutron kerma falls below the neutron threshold of 600 KeV, and is hence unaccounted for. To provide additional integral data below 600 KeV DREO uses a pair of boron-triflouride counters (one cadmium-covered) and fits a parametric relation (of the form AE^p) to the measured data, assuming piecewise spectral continuity at 600 KeV with the NE-213 determination [3]. Integral quantities are subsequently estimated by folding the parametric relation against appropriate energy-dependent fluence-to-kerma (or dose) response functions, as required. (See Appendix C for further details).

Fluence and kerma data have also been obtained (primarily by APRD) using various integral counters of up to sixteen litres in volume [1,4,10] Total kerma is measured using tissue-equivalent ionization chambers, from which may be subtracted gamma-ray kerma measured by Geiger-Müller counters to predict neutron-only kerma. DREO has also on occassion employed microdosimetric techniques in which the deposition of energy to a very small volume of tissue-equivalent gas is measured as a function of LET (linear energy transfer), enabling the separate estimation of gamma-ray (low LET) and neutron (high LET) kermas.

Measurement of neutron fluence above 3 MeV is routinely performed by APRD using activation of sulphur to phosphorus-32 through the (n,p) reaction, with calibration against Californium-252 neutrons [16]. More recently, Bonner-sphere neutron determinations have been initiated by APRD [8,9]. In this technique the spectral variation of neutron detection efficiency of a small lithium-6 iodide scintillator is successively modified by surrounding it with polyethylene spheres of different diameters. Although always sensitive to some extent to neutrons of all energies, the addition of polyethylene shifts the peak response of the scintillator from thermal energies (0.025 eV) gradually through to near 10 MeV when the largest sphere (12" diameter) is used. The eight counting-rates so measured may be used either to obtain a low-resolution estimate of the neutron spectrum by unfolding, or alternatively to measure the consistency with neutron spectra obtained by other methods by folding the a-priori neutron spectra against known Bonner response functions, then comparing both calculated and observed counting rates [8].

In spite of the large number of techniques that have been applied to measure integral quantities at APRD, a very high degree of experimental consistency is apparent - suprisingly so when consideration is made of the fact that very few share common detector calibrations. (See Appendix G for a listing of all reported integral measurements at APRD.)

2.4 Soil Composition

Physical and chemical attributes of APRD soils have been determined by APRD and WWD in March of 1978 [1,2] and by DREO in July of 1982 (Appendix I). Reported density has varied from 1.5 to 2.1 grams per cubic centimeter and soil moisture content from 12 to 40 weight-percent. Reported elemental composition also varies widely, although this is probably due more to the vagaries of chemical analysis than variation in the soil itself. Appendix I lists all reported soil composition for APRD, including recent DREO analyses.

3.0 EXPERIMENTAL RESULTS

3.1 Review of 1980 Spectrometry

By the end of 1980 three separate groups had made free-field spectral measurements, namely APRD, WWD and DREO. For the three ranges of commonality (100, 170 and 300 meters) neutron and gamma-ray spectral determinations are shown by way of comparison in Figures 2 through 7. Normalization in all cases is per source neutron, employing the then-current

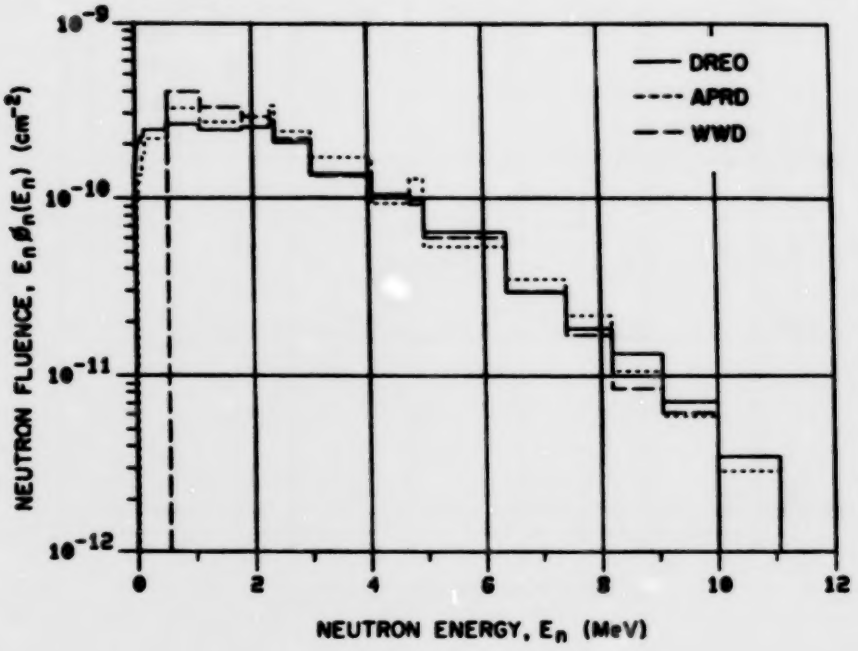

Figure 2 - Measured Neutron Spectra at a Ground Range of 100 Meters

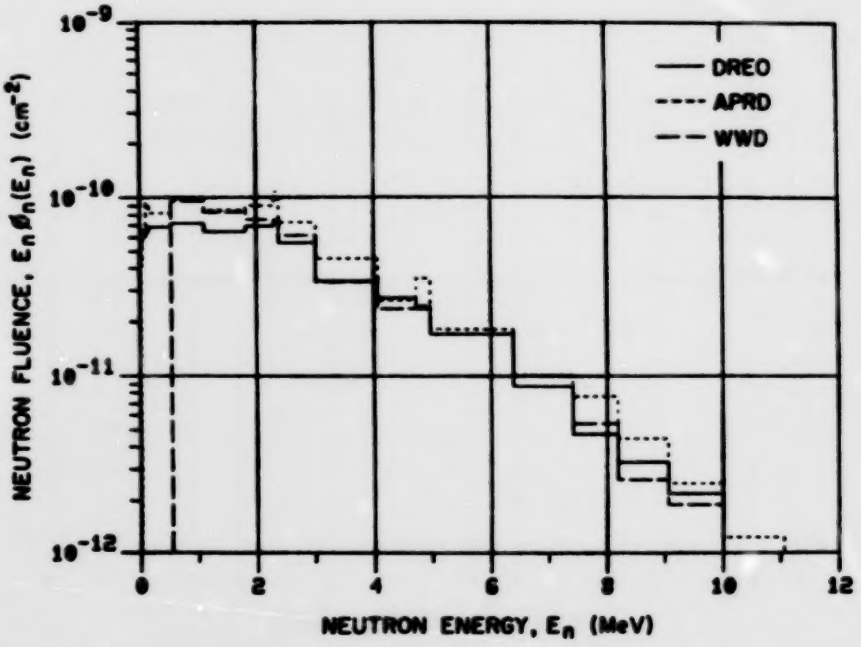

Figure 3 - Measured Neutron Spectra at a Ground Range of 170 Meters

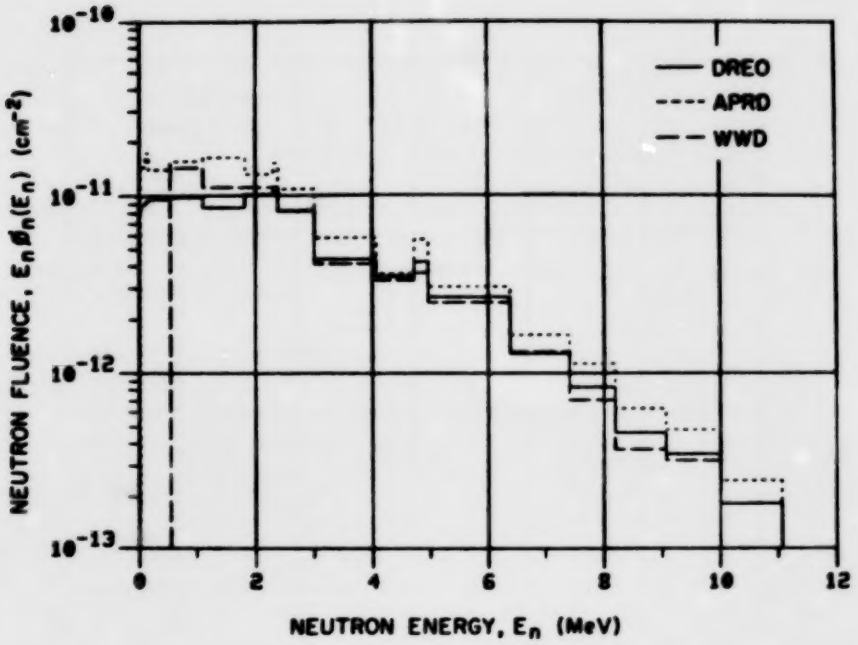

Figure 4 - Measured Neutron Spectra at a Ground Range of 300 Meters

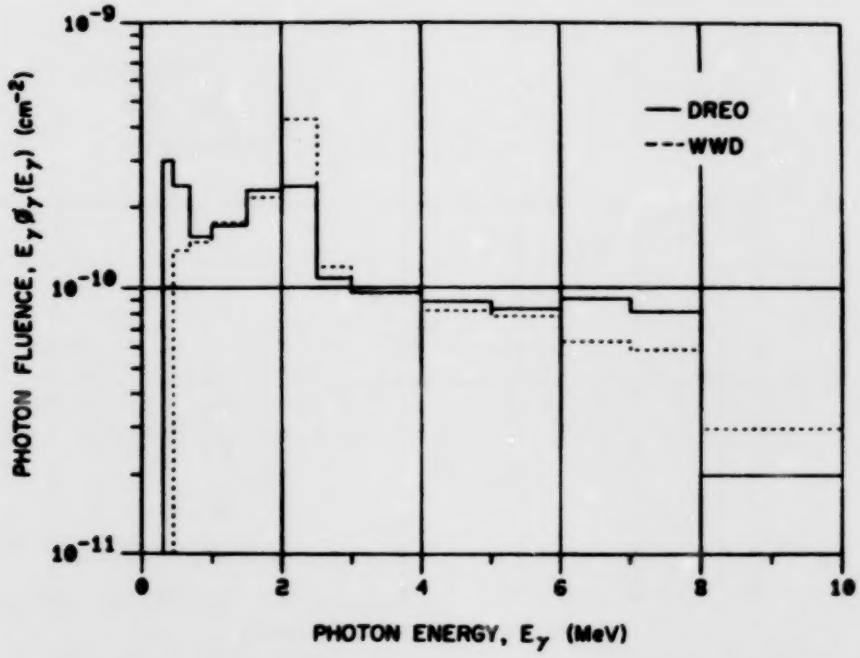

Figure 5 - Measured Gamma-Ray Spectra at a Ground Range of 100 Meters

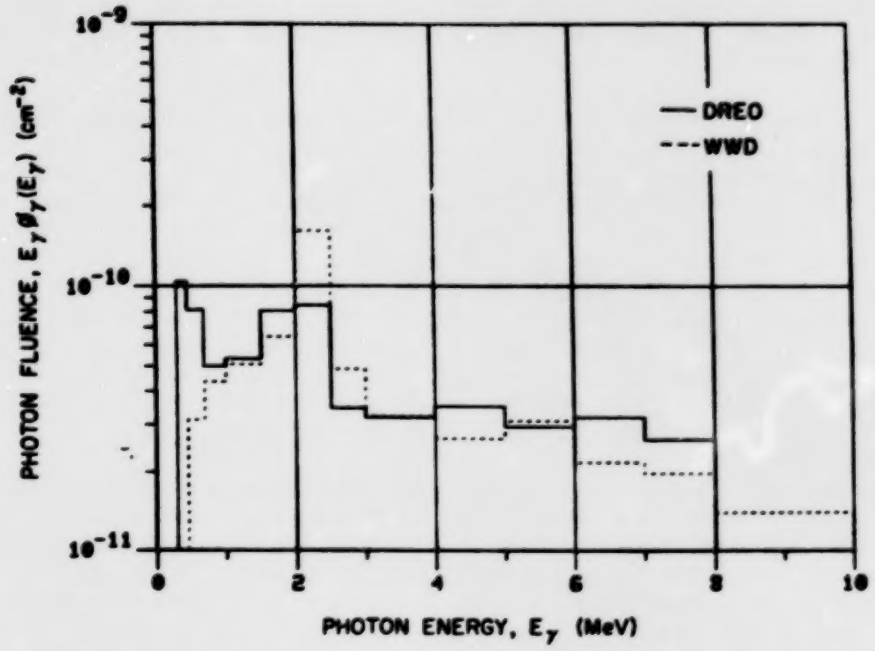

Figure 6 - Measured Gamma-Ray Spectra at a Ground Range of 170 Meters

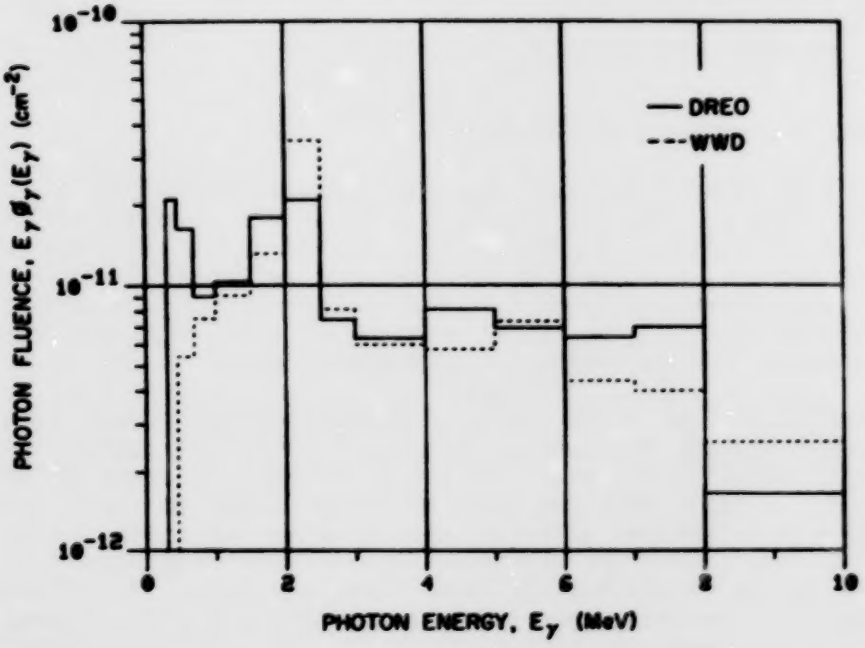

Figure 7 - Measured Gamma-Ray Spectra at a Ground Range of 300 Meters

source yield of 1.28×10^{17} neutrons per kilowatt-hour. (Results of the additional DREO measurements at 15, 400 and 1080 meters may be found in Appendices A through F, as part of a comprehensive reporting of DREO measurements to date.)

Above a neutron energy of 2 MeV there is reasonable agreement amongst the three groups. APRD fluences are somewhat higher in general than those of WWD and DREO, which are in close agreement with each other. In contrast, below 2 MeV here are significant differences apparent in the comparisons. DREO-estimated neutron fluence is systematically lower than either APRD or WWD, at all three ranges. At the closest distance of 100 meters WWD results exceed those of APRD; at 170 meters they are in close agreement; and at 300 meters APRD results instead exceed those of WWD. The noted variations should be ascribed to differences either in measurement technique or data analysis between the three groups, rather than differences in air or soil conditions at the time of measurement, which are thought not to affect the spectra to the extent necessary to explain these variations [14].

Gamma-ray spectra measured by WWD and DREO show agreement which is reasonable overall, with some significant differences. Below 1 MeV DREO estimates almost twice as many photons as does WWD. At the 2.2 MeV hydrogen capture line WWD estimates more fluence than does DREO - this may be due either to better WWD resolution or to a higher soil moisture content. Between 2.5 and 6 MeV the two groups are in very close agreement at all ranges. Between 6 and 8 MeV DREO estimates a greater fluence than WWD, but the reverse is true above 8 MeV. At these higher energies gamma-ray spectroscopy becomes more difficult due to the deterioration in shape of the NE-213 response functions, most of the sensitivity resulting from interactions which deposit little energy near the diagonal of the response matrix, most of it appearing at much lower energies. The greater difficulty in interpreting this data probably explains the noted differences above 6 MeV.

3.2 1981 Measurements at 1080 Meters

As part of other investigations, DREO measured free-field spectra in 1981 at three ranges: 179, 260 and 1080 meters. Measurements at the two shorter ranges were made with the reactor inside its silo, consequently these will be excluded from further consideration, although the results are reported in Appendices A through F. The measurement of 1080 meters was however made with the core positioned outside the silo, with the intent to test the reproducibility of the single 1980 measurement.

Weather conditions at the times of measurement were almost identical (see Appendix A) as was the time of year (mid October). Neutron spectra resulting from the two measurements are shown in Figure 8, gamma-ray spectra in Figure 9. In each case the vertical range shown for each spectrum encompasses the best spectral estimate, plus-or-minus one standard error due to statistical fluctuation as estimated by the unfolding technique. In neither case is any statistically-significant variation in differential spectrum apparent. Neutron kermas derived from these spectra (Appendix G) agree to within 6%, gamma-ray kermas within 4%, and total kerma within 2%. Estimated neutron fluences above 3 MeV differ by 15%, but even this is thought not significant due to the greater unfolding errors at the higher energies. Good precision is therefore demonstrated at 1080 meters, which is effectively the maximum range for NE-213 spectrosopy at APRD, given current core power levels.

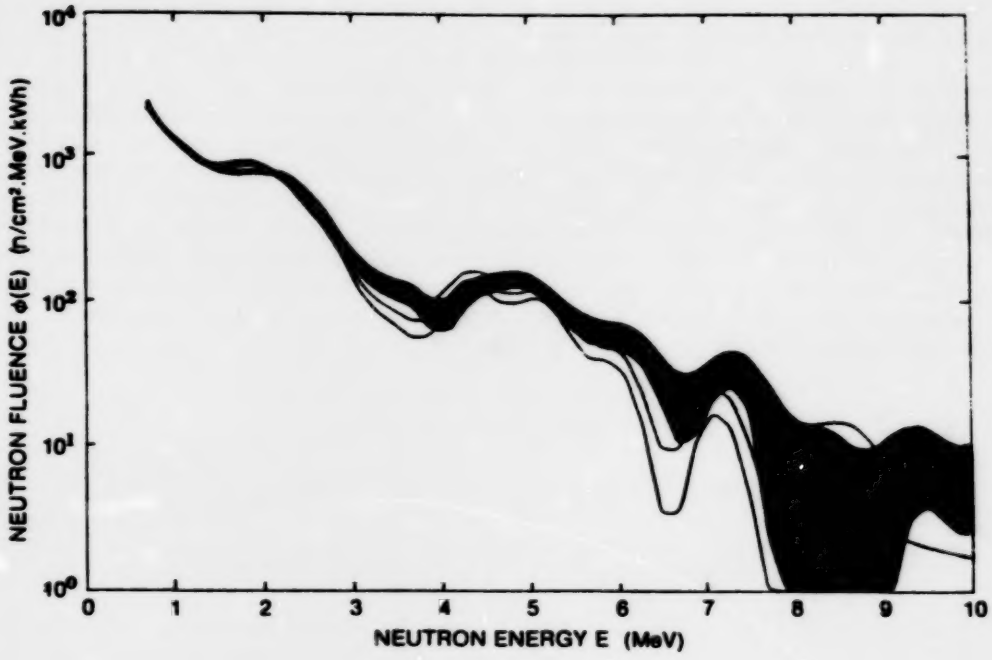

Figure 8 - Neutron Spectra Measured at 1080 Meters in 1980 (Solid) and 1981 (Open)

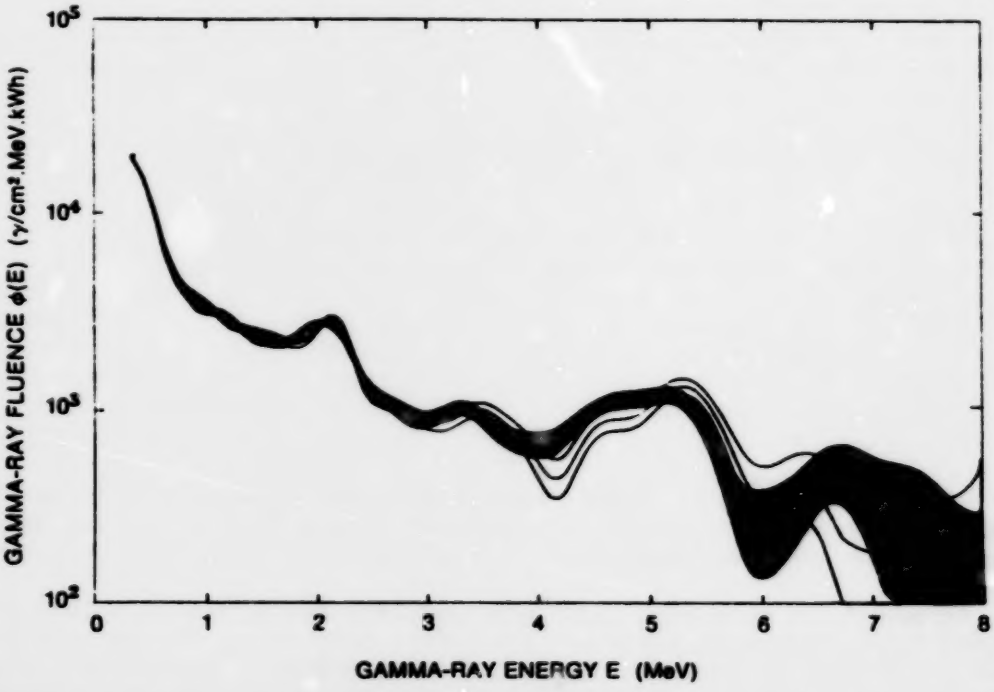

Figure 9 - Gamma-Ray Spectra Measured at 1080 Meters in 1980 (Solid) and 1981 (Open)

3.3 Bonner-Sphere Determinations

Neutron spectra estimated by APRD in 1981 and 1982 using Bonner-sphere techniques are not reproduced here, instead they may be found in a recent 1982 APRD publication [8]. Tabulated below, however are the counting-rate ratios determined by dividing calculated counting-rates by experimentally-observed counting-rates. The calculated counting-rates were determined at APRD by folding the energy-dependant response functions of each sphere-detector combination with previously-measured DREO neutron spectra and integrating over energy. Thus the listed counting-rate ratios are a measure of consistency between APRD Bonner-sphere measurements and DREO spectral determinations.

TABLE 1

BONNER-SPHERE COUNTING-RATE RATIOS

SPHERE	PRIMARY SENSITIVITY (MeV)	COUNTING-RATE RATIO	
		170 m	1080 m
Bare	$0 - 10^{-5}$	0.90	0.92
Cd-covered	$0.5 \times 10^{-6} - 10^{-5}$	1.04	0.96
2"	$0 - 10^{-4}$	0.94	0.82
3"	$0 - 10^{-2}$	1.06	0.90
5"	0 - 5	1.11	0.99
8"	0.5 - 10	1.08	0.99
10"	1 - 15	1.13	1.06
12"	2 - 20	1.07	1.05
Mean		1.04±8%	0.96±8%

The energy ranges listed over which each sphere is primarily sensitive are highly approximate [27] and shown only to give an indication of the important energies involved.

Agreement is apparently good and certainly consistent to within the estimated Bonner-sphere accuracy of ±12%. This tends to verify not only the DREO-measured neutron spectra using the NE-213 system at 170 and 1080 meters, but also the overall validity of the parametric equation used to analyse the BF_3 data below 600 KeV.

3.4 High Temperature and Humidity Measurements

Measurements obtained at 1080 meters in 1980 and 1981 were characterized by similarly moderate weather conditions. In 1982 another determination was made, this time during a hot, moist period (July) to try to obtain information on the sensitivity of air-transmitted spectra to atmospheric conditions. Average atmospheric parameters of importance prevailing at the time of each experiment are tabulated below.

TABLE 2

ATMOSPHERIC CONDITIONS PREVAILING DURING MEASUREMENTS AT 1080 METERS

PARAMETER	1980	1981	1982	Units
Air density	1.228	1.229	1.157	g/litre
Temperature	16	18	29	°C
Vapour density	8.4	6.4	21.1	mg/litre

Air density during 1982 was lower by 6% than in previous years, temperature was higher by 13-16 °C, and atmospheric moisture content higher by approximately a factor of three. In spite of these significant changes in atmospheric conditions, little change is apparent in the measurement of neutron and gamma-ray spectra (Figures 10 and 11). It would appear that the increase in atmospheric moisture content has been approximately compensated for by the decrease in air density.

Total neutron kerma derived from the 1982 spectrum is increased by 4% over the average of 1980 and 1981 measurement; gamma-ray kerma is similarly increased by 11%; and total kerma increased by 7%. Of these only the increase in gamma-ray kerma is judged to be statistically significant (marginally) and this increase is probably due to increased neutron capture by hydrogen in the more moist atmosphere. An increase in > 3 MeV neutron fluence of 7% is judged not to be significant, compared to experimental error.

APRD Bonner-sphere determinations made concurrently with the DREO measurements similarly indicated no consistent or significant spectral changes attributable to differences in weather conditions [9].

3.5 Integral Dosimetry

Many more measurements of integral quantities at APRD (129) are available than are spectroscopic determinations. A comprehensive listing of these quantities may be found in numerical form in Appendix G and plotted as functions of range in Figures 12 (neutron fluence > 3 MeV), 13 (neutron kerma), 14 (gamma-ray kerma) and 15 (total kerma). In these graphs the

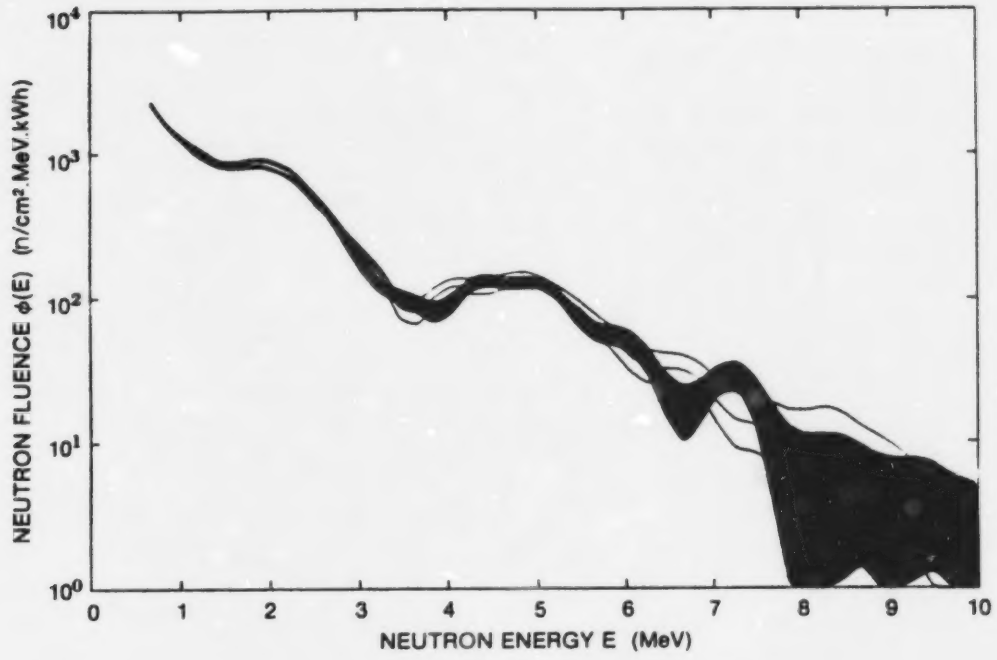

Figure 10 - Neutron Spectrum Measured in 1982 at 1080 Meters (Open) Compared to the Average of Previous Measurements (Solid)

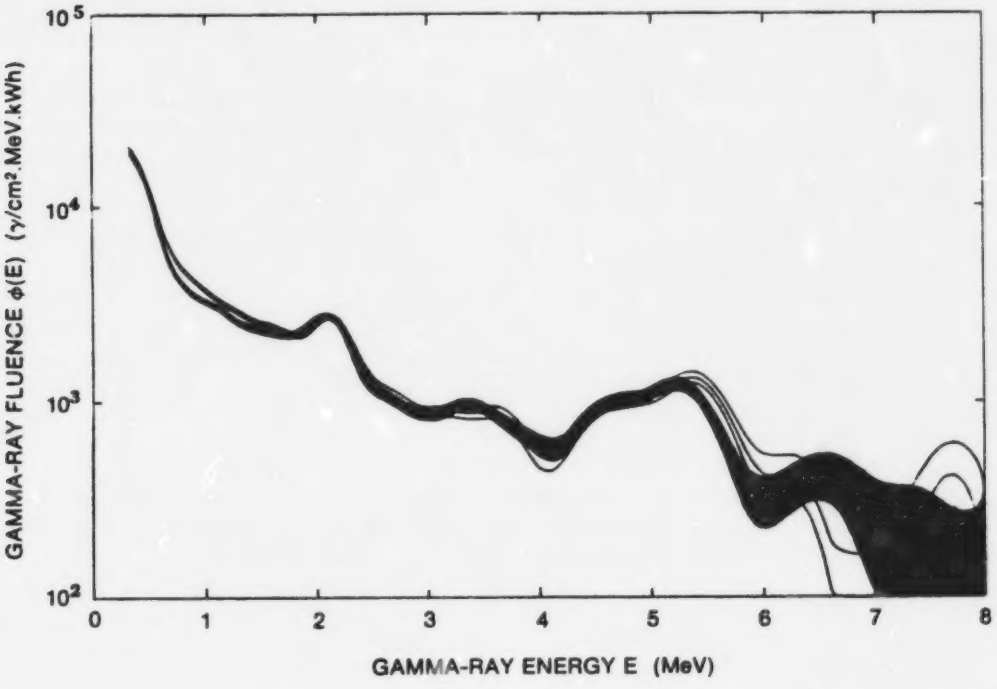

Figure 11 - Gamma-Ray Spectrum Measured in 1982 at 1080 Meters (Open) Compared to the Average of Previous Measurements (Solid)

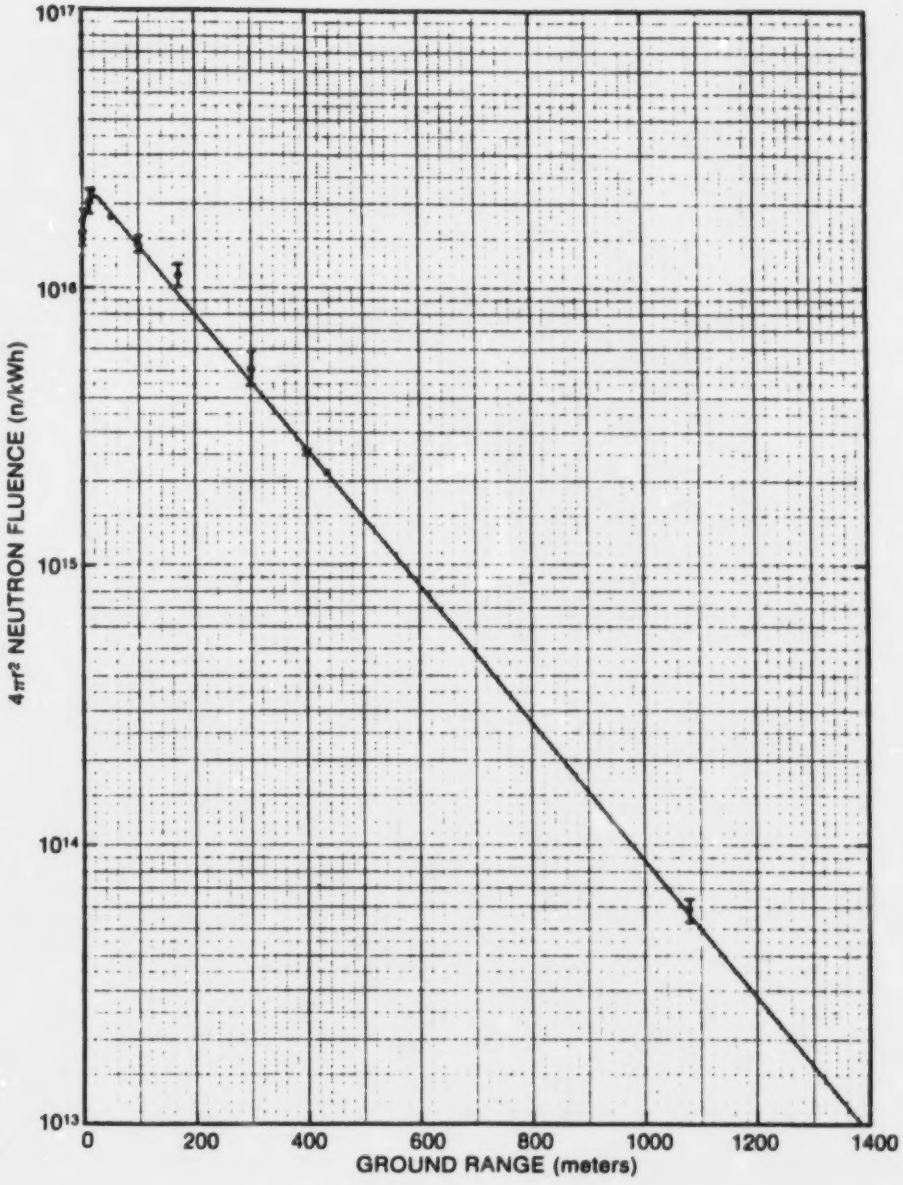

Figure 12 - Measured Variation of Neutron Fluence above 3 MeV with Increasing Ground Range

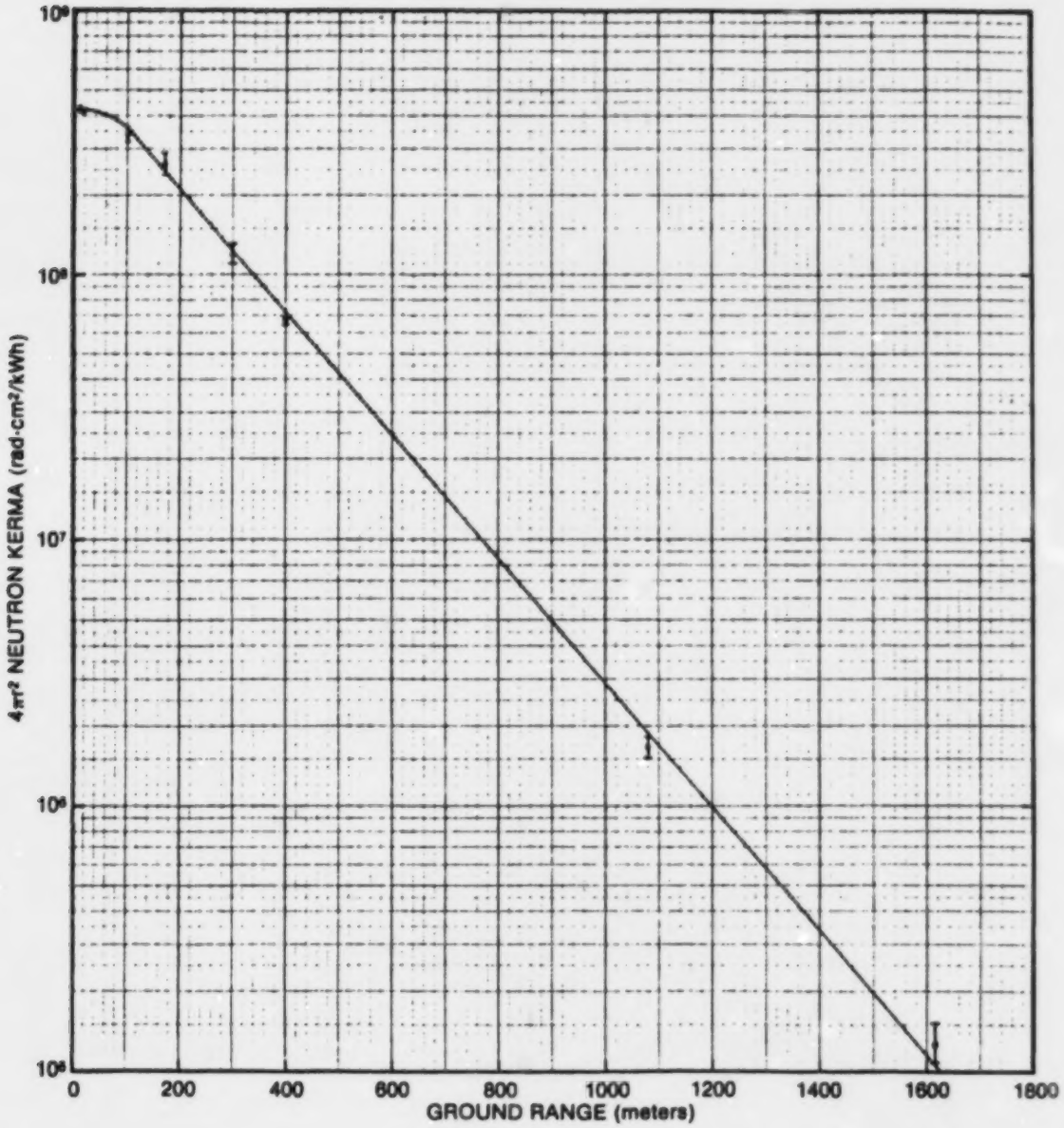

Figure 13 - Measured Variation of Neutron Tissue-Kerma with Increasing Ground Range

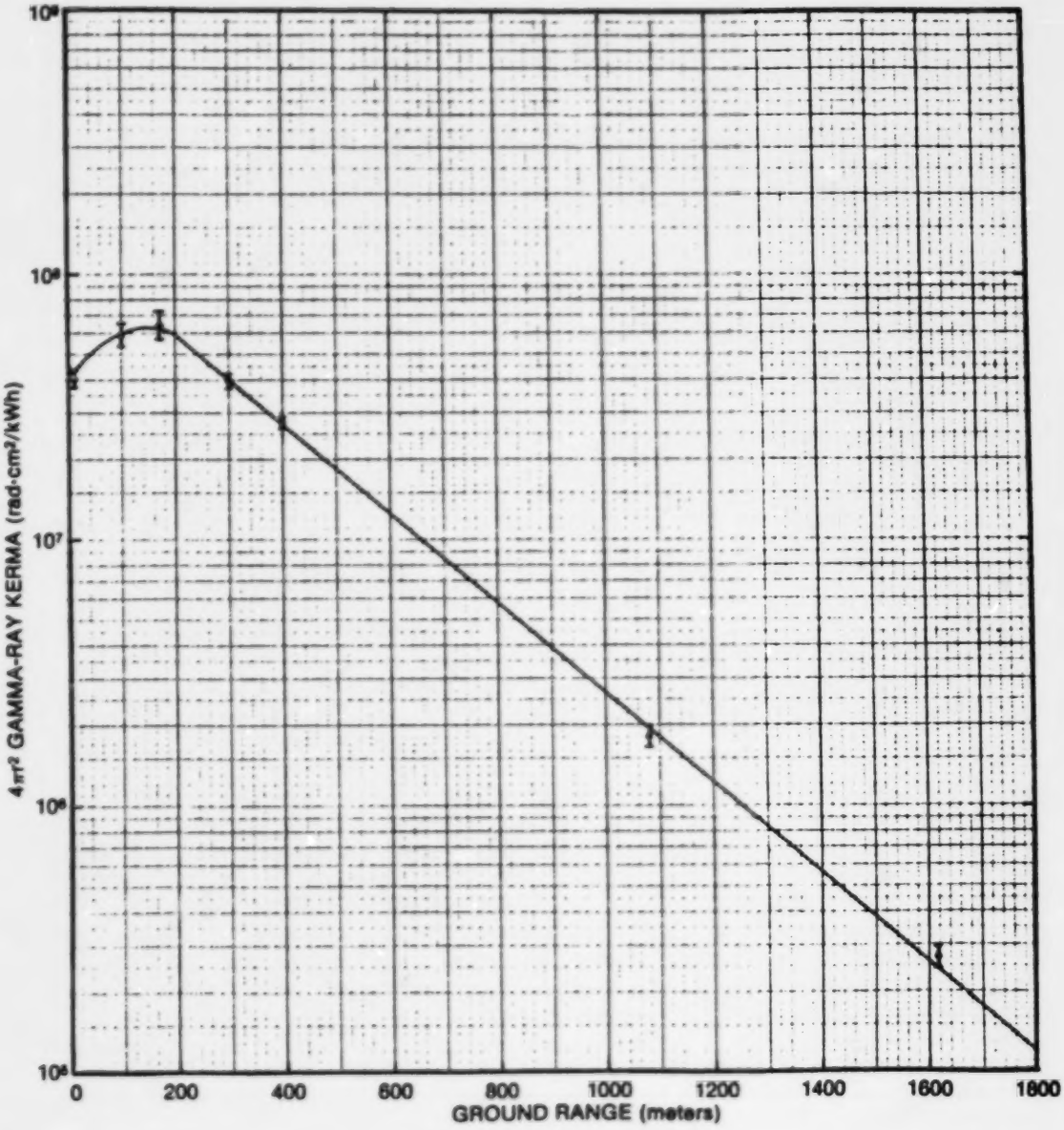

Figure 14 - Measured Variation of Gamma-Ray Tissue-Kerma with Increasing Ground Range

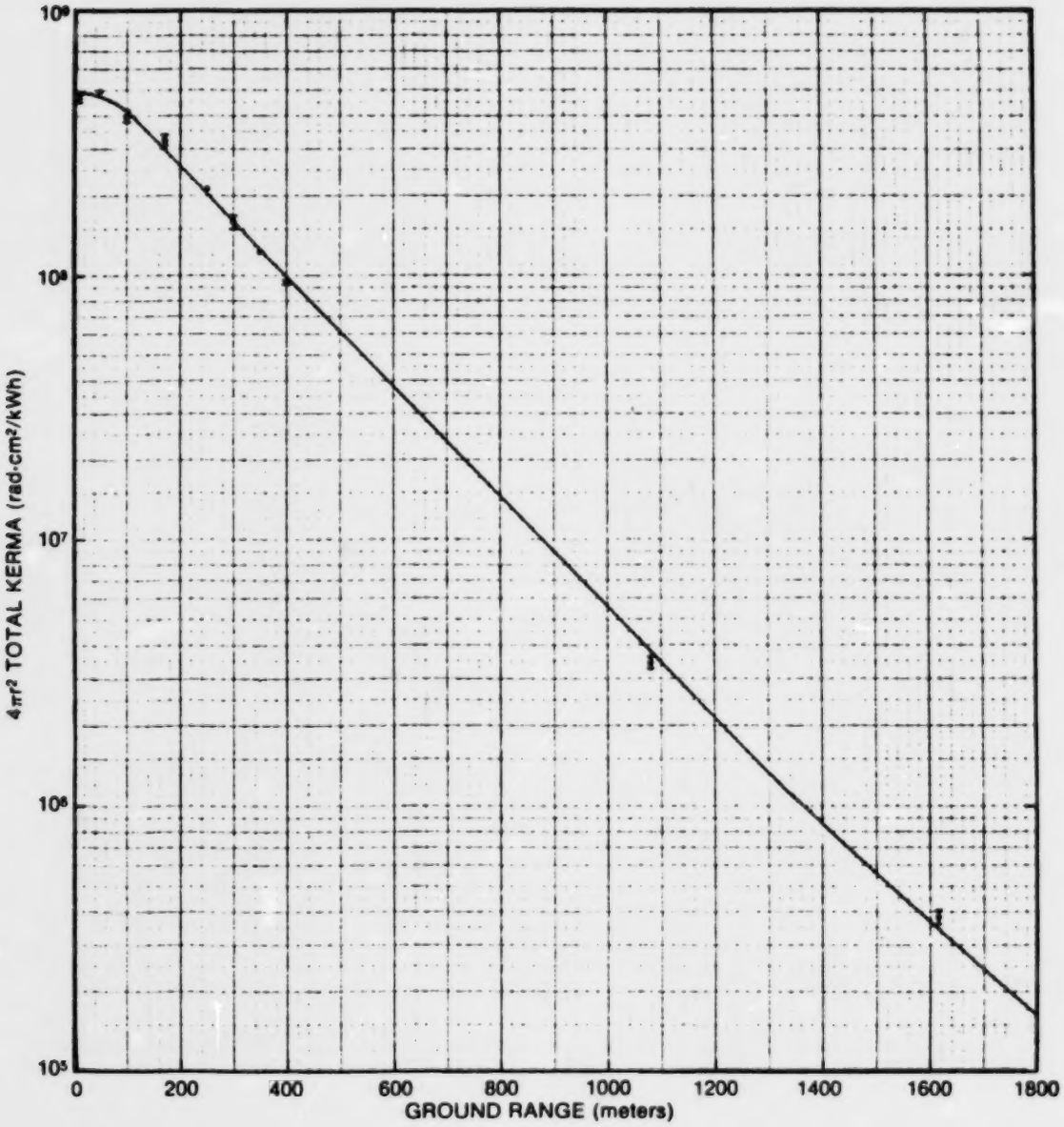

Figure 15 - Measured Variation of Total Tissue-Kerma with Increasing Ground Range

plotted quantities have been multiplied by $4\pi r^2$ at each measurement position in order to eliminate strictly geometrical attenuation with distance. The "error bars" shown correspond not to estimated experimental error but instead observed standard deviations (sample definition) amongst all common measurements at each range. (A point without an associated deviation indicates a single measurement.) The plotted lines are not theoretically-derived, instead these are best-fit exponentials beyond the ranges at which equilibrium attenuation appears to be achieved, and smooth curves ("optical") at shorter ranges.

Neutron fluence above 3 MeV (Figure 12) increases approximately 20% in the first twenty meters from the core (presumably due to ground-return) thereafter decaying exponentially with distance with an indicated relaxation length of 177 meters. Consistency amongst the various measurements is generally better than 10%.

Neutron kerma (Figure 13) decreases monotonically with distance, equilibrium attenuation appearing to start at about 100 meters, with a characteristic relaxation distance of 187 meters. Presumably ground-return neutrons are reflected back at sufficiently lower energies that an initial increase in $4\pi r^2$ neutron tissue-kerma is not observed. Neutron kerma measurements are self-consistent to approximately the same degree as are neutron fluences, or generally better than 10%. Recent APRD Bonner-sphere [11] and ion-chamber Geiger-Müller [10] measurements at 1618 meters are also apparently in good agreement with measurements at shorter ranges.

Initial enhancement of gamma-ray kerma (in the $4\pi r^2$ sense) is apparent to approximately 150 meters, after which attenuation with a relaxation length of 259 meters is indicated (Figure 14). The increase in gamma kerma at short range is due to radiative neutron capture in the air and ground, and the greater relaxation length (compared to neutron kerma) to the longer mean-free-path in air. Observed experimental consistency is generally between 5 and 10 percent at most ranges.

In the case of total tissue kerma (Figure 15) the plotted line represents the sum of previously plotted neutron and gamma-ray kermas. Experimental consistency is everywhere better than 6% and often less than this. Since this is somewhat superior to the consistency observed amongst either neutron or gamma-ray measurements, it may be suspected that some mis-identification of particle type occurs in individual measurements. In particular DREO estimates total kerma by adding individual contributions as measured by the same detector (using pulse-shape discrimination between particle types), consequently an overestimation of one component could be compensated for by a similar underestimation of the other component. APRD measurements of total kerma are instead made directly using tissue-equivalent ionization chambers of large volume (4 or 16 litres), however the estimation of neutron kerma is accomplished by subtracting gamma-kerma as measured by Geiger-Müller counters. Greater variance is therefore expected in the measurement of neutron kerma since this is determined by numerical difference, and hence subject to greater statistical fluctuation. It should be noted, however, that no statistically-significant systematic over- or under-prediction may be attributed to either of the above-mentioned techniques as a result of measurements made to date at APRD. All that may be concluded is that measurement of total kerma appears to be generally more precise than measurement of either neutron or gamma-ray kerma alone.

The overall consistency observed in the measurement of integral quantities at APRD compares favourably for instance, with the 7 to 8% variations observed by the 1975 European neutron dosimetry intercomparison project [28] - especially considering the much less-well controlled experimental conditions at APRD, and the five-year span of the measurements.

The good agreement between APRD TE-GM determinations of neutron kerma and those of DREO employing a combination of NE-213 and BF_3 detectors (see Appendix G) is at variance with previously-noted spectral differences below 2 MeV between DREO, APRD and WWD-determined neutron spectra (Figures 2-4). Between 0.11 and 2.3 MeV of neutron energy falls approximately 65% of the neutron tissue-kerma (as determined at 170 meters by DREO). Were the DREO-determined neutron spectra at 100, 170, and 300 meters deficient by the 25 to 35% indicated by comparison to WWD and APRD determined spectra in this energy range, then it would be expected that DREO estimates of total neutron kerma should be similarly deficient by approximately 20%, in a systematic manner when compared to other integral measurements. This is in fact not observed - DREO estimates of neutron kerma are at all ranges within 7% of the corresponding mean values. Compensation by differences at energies outside the cited range is unlikely since only 35% of neutron kerma is available to compensate, and the DREO-measured neutron spectra have been shown to be in good agreement with Bonner-sphere observations [8].

3.6 Discussion

The varied techniques employed by the three groups to measure integral quantities at APRD are in good agreement with each other - observed variances are no more than would be reasonably expected given current knowledge of radiation dosimetry, even under more favourably-controlled experimental conditions.

The less-numerous neutron spectra measured at APRD, however, do exhibit significant, systematic differences at ranges where commonality exists - APRD is generally higher than the others at all energies, WWD and DREO are in good agreement above 2 meV but below this energy DREO is generally lower by 25 to 35%. All three groups use similar instrumentation and pulse-shape discrimination techniques. WWD and APRD used identical unfolding codes and neutron response matrices, however DREO codes and response matrices differed. A possibility of unfolding bias therefore exists between DREO and APRD/WWD results; however for the opposite reason APRD and WWD neutron spectra should be in better agreement with each other than currently observed. DREO results are supported by consistency with Bonner-sphere observations, integral dosimetry and demonstrated spectral and absolute reproducibility of Cf^{252} neutron spectra (Appendix J). It is presently unclear, however, why the measurements of neutron spectra similar to that from Cf^{252} do not agree better. Only through a well-controlled spectral intercomparison between the three groups may it be resolved whether the noted differences are in fact due to experimental bias or instead merely due to the vagaries of NE-213 neutron spectroscopy.

Differences between WWD- and DREO-measured gamma-ray spectra are also evident, the most significant occuring below 1 MeV where differences of a

factor of two are observed. As was discussed regarding neutron spectra, these differences are presently unexplained, but could be put into perspective by a better-controlled intercomparison.

At 1080 meters, good reproducibility has been demonstrated both in the measurement of neutron and gamma-ray spectra, and also integral quantities, over extended time periods. The influence of variations in atmospheric conditions has been shown to be minimal, although low-temperature measurements might also be made to support this claim further.

4.0 THEORETICAL CALCULATIONS

4.1 Previous ORNL and DREO Calculations

Prior to 1981 two calculations of the free-field radiation environments at APRD were available - one performed in 1979 at ORNL [6] and one in 1980 performed at DREO [3]. Both employed the DOT radiation transport code [29], interaction data from the 1975 DNA library [30], neutron and gamma-ray source spectra as predicted by an earlier ORNL core-calculation [2], and the then-accepted source normalization factor of 1.28 x 10^{17} neutrons per kilowatt-hour [2]. The ORNL calculation used an S8 angular quadrature and a realistic atmospheric composition including humidity, but was limited to a maximum range of 500 meters. The DREO calculation used a coarser angular quadrature (S6) and spatial mesh, and a dry-air approximation, but extended the ground range to 1500 meters. In spite of the different approximations employed agreement in the integral sense was good, although the DREO-calculated gamma-ray spectra were probably deficient due to discrete ray-streaming effects [3]. Calculated neutron spectra, however, were in good agreement.

Comparison to experimental measurement [3,6] indicated that theoretical predictions of neutron spectra were softer than observed (fewer neutrons above 2 MeV but more below this energy). Surprisingly, agreement was best at the farthest measurement position of 1080 meters. Calculated gamma-ray spectra were also softer than observed and agreement best at 1080 meters, but it must be noted that the DREO calculations were influenced to some degree by discrete ray-streaming effects.

4.2 Recent LANL, SAI and LLNL Calculations

In 1982 a group at LANL recalculated the APRD neutron radiation environments [14], using a continous-energy Monte Carlo transport code (MCNP) and interaction data derived from ENDF/B-V. Only neutron spectra above 0.55 MeV (the lower NE-213 threshold) were predicted, but concurrently the effects of ground water content, ground density, relative atmospheric humidity and revised source spectra were examined, as were drastic changes in the total cross sections of nitrogen and oxygen. Their study concluded that integral quantities were predicted with reasonable accuracy, but that spectral disagreement persisted which could not be readily resolved by postulated changes in the above-mentioned parameters. Calculated neutron

spectra were found to be uniformly softer than measured; as were similar calculations [31] performed to compare with the ORNL "broomstick" and LLNL "pulsed-sphere" experiments, in which neutron transport through samples of liquid nitrogen and liquid oxygen was studied.

Also in 1982, SAI performed calculations [13] of the radiation environments at APRD for comparison with experimental measurement using discrete-ordinates techniques (DOT-SAI), the DNA data library [30] and the revised LANL-calculated neutron source spectrum [18]. Calculations of the importance of atmospheric composition on neutron transport were originally made using one-dimensional models (ANISN [32]) and indicated that atmospheric conditions prevailing at the time of each groups' experiments made little difference to the calculations out to a 500 meter range, but at one kilometer significant differences (±15%) were apparent. Subsequent DOT calculations used atmospheric conditions characteristic of the DREO experiments as these led to the intermediate ANISN results at one kilometer.

Calculated and measured neutron and gamma-ray kermas were concluded to be in generally good agreement with each other. Calculated neutron spectra were found to be in better agreement with the measurements of WWD than those of either APRD or DREO. It was postulated that this may have been due to differing soil water contents typical at the time of each groups measurements (WWD measurements were made in March of 1978 with ground snow cover of 35 l/m^2 [1]) or alternatively to unfolding errors on the part of DREO, primarily below a neutron energy of 3 MeV. Between 0.5 and 3 MeV the WWD spectra were in good agreement with SAI calculations, however APRD's were higher and those of DREO lower. Below 0.5 MeV the SAI calculations were, however, found to be in good agreement with the parametric BF_3 determinations of DREO.

Gamma-ray spectra were also in better agreement with the measurements of WWD than those of DREO, but this was somewhat expected since soil conditions at the time of the WWD experiments were employed in the calculations. The greater intensity of the 2.2 MeV capture gamma-ray from hydrogen apparent in the WWD spectra (when compared to DREO spectra) was cited as evidence that ground moisture content was in fact higher. Improved agreement with DREO spectra at 1080 meters also indicated that soil moisture was relatively less important at the longer experimental ranges (the reduced intensity of DREO-measured 2.2 MeV gamma-rays at 1080 meters supports this observation - see Appendix B).

LLNL has similarly calculated [12] the APRD environments using the DOT-4 code and LLNL data-libraries. At the time of writing, only integral dosimetry data are available, however these will be seen to be in reasonable agreement with corresponding experimental values.

4.3 Comparison to Experimental Spectroscopy

In Figures 16 through 18 LANL calculations of neutron spectra are compared to DREO measurement at each of three ground ranges: 170, 400 and 1080 meters. Two experimental curves are shown. The upper curve corresponds to the unfolded spectrum plus one standard error, normalized to source neutrons using the factor 1.10×10^{17} source neutrons per kilowatt-hour. The lower curve indicates the unfolded spectrum minus one standard

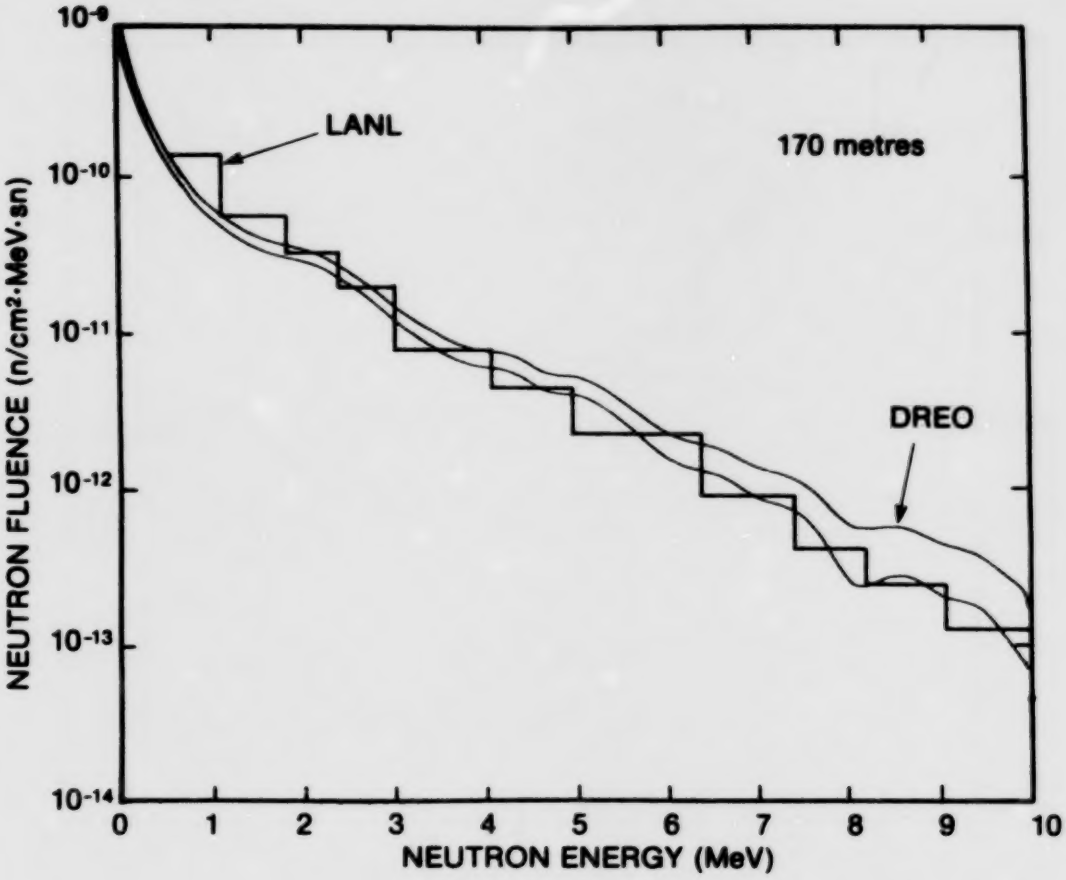

Figure 16 - Comparison of LANL-Calculated and DREO-Measured Neutron Spectra at 170 Meters

error, normalized by the factor 1.28 x 10^{17} source neutrons per kilowatt-hour. Thus the two curves define a range of possible experimental values taking into consideration both unfolding errors and source yield uncertainty. Comparisons at 100 and 300 meters are not shown, however they follow generally those at 170 and 400 meters, respectively.

At the first two measurement locations shown (Figures 16 and 17) agreement is good in an integral sense, however the calculated spectra are softer than measurement would indicate. Above 2 MeV calculations fall generally within the range of plausible experimental values, however below this energy significant overprediction is apparent (by as much as 70%). It should be noted that at this range (and below 2 MeV) the APRD/WWD results similarly exceed DREO by up to 40% - i.e. in the direction of improved agreement with LANL calculations, however the conclusion of overproduction by calculation is still true.

At the farthest measurement position (Figure 18) agreement between the DREO measurements (average of 1980 and 1981 determinations) and LANL

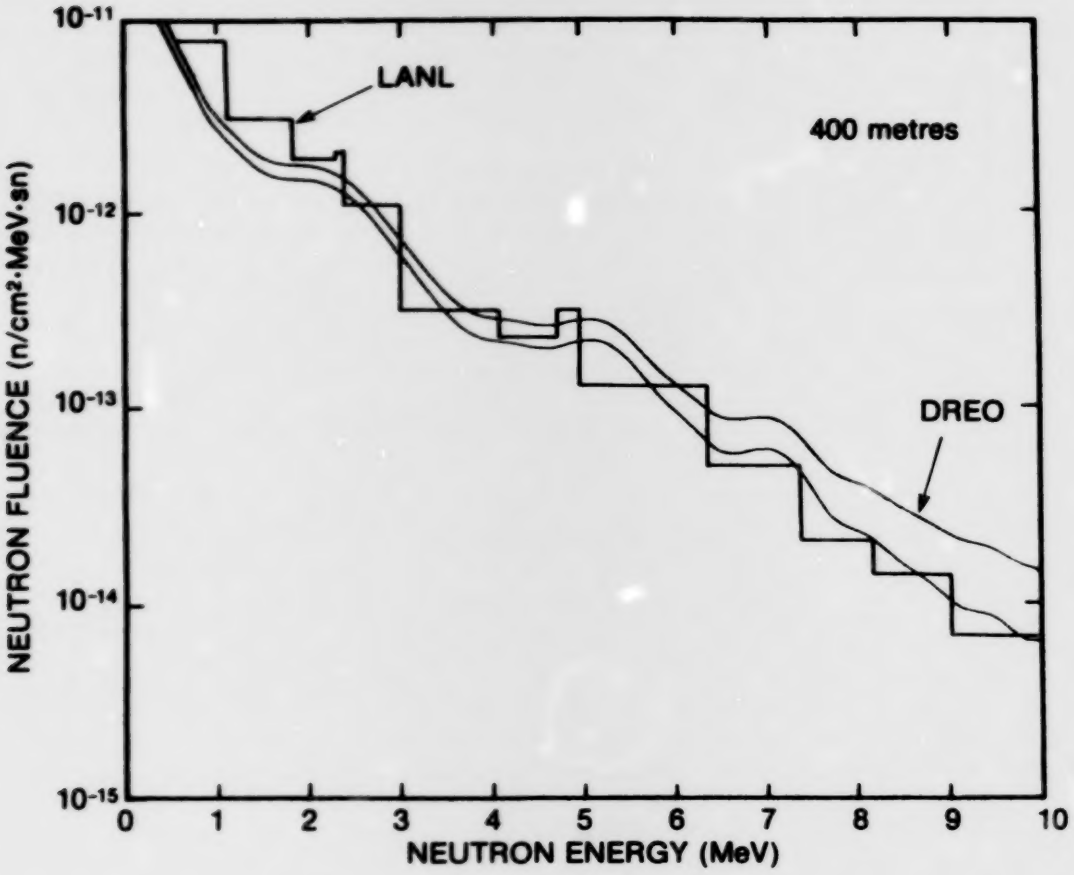

Figure 17 - Comparison of LANL-Calculated and DREO-Measured Neutron Spectra at 400 Meters

calculations is significantly improved, both in spectral hardness and intensity. Agreement between 1 and 2 MeV is good, however below 1 MeV a persistent overprediction of about 40% is apparent.

The indication of improved agreement at the farthest range is admittedly puzzling. One possible explanation is that the neutron source spectrum requires revision. At shorter ranges the characteristics of the source will dominate the air-transported measured spectrum, whereas at longer ranges the spectral details of the source are progressively overcome as transported neutrons relax into a spectrum determined primarily by the scattering laws of the intervening media. Increasing disagreement as the source is approached would thus suggest the core calculation as being at fault, rather than the air-transport calculation. It therefore would be of considerable interest (were it possible) to perform NE-213 spectroscopy beyond 1080 meters to determine whether the agreement between calculation and experiment observed at 1080 meters persisted, or alternatively worsened in a sense opposite to that observed at shorter ranges (i.e. continued to soften with respect to corresponding calculations). It should be noted however, that Bonner sphere measurements at 1618 meters [11] do not indicate any significant change in neutron spectrum compared to that measured at 1080 meters.

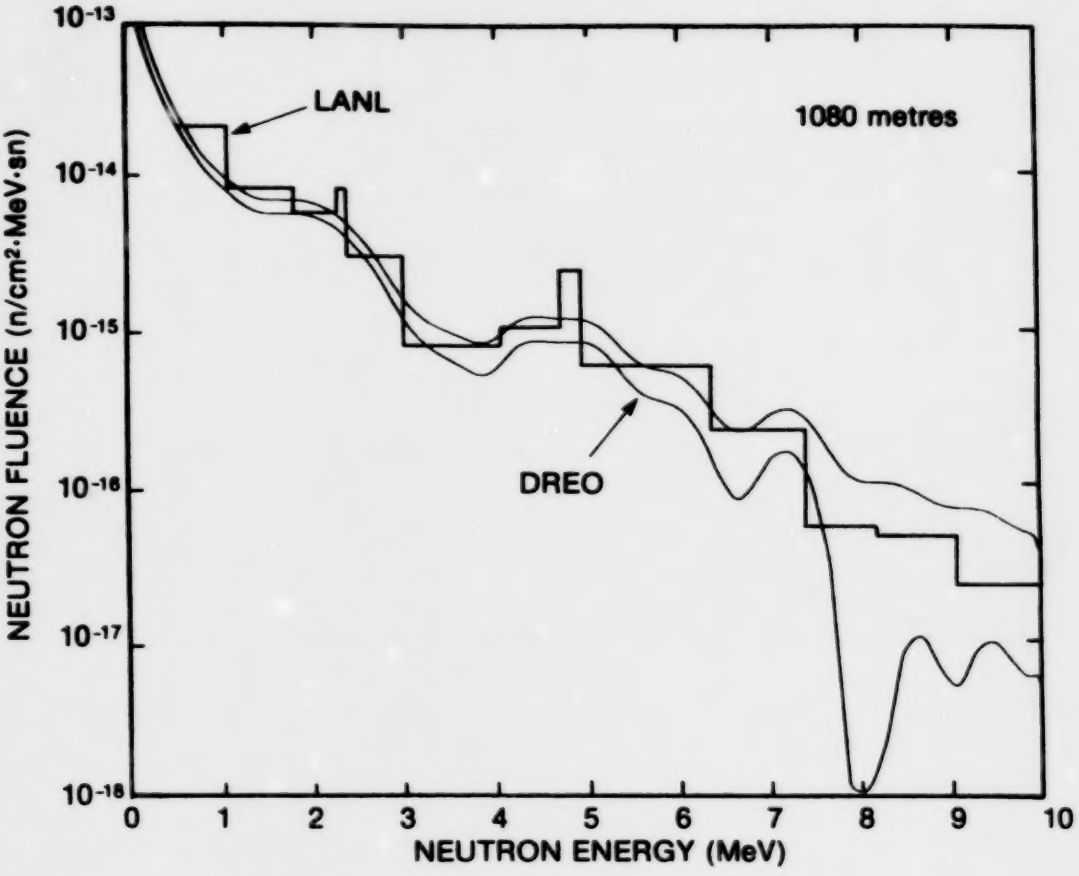

Figure 18 - Comparison of LANL-Calculated and DREO-Measured Neutron Spectra at 1080 Meters

Corresponding SAI calculations of neutron spectra are compared to DREO measurements in Figures 19 through 21, also for ranges of 170, 300 and 1080 meters. Relative to the previous comparisons with LANL calculations, agreement between experimental and theoretical spectra is improved somewhat above 2 MeV, but overprediction of measurement persists between 0.5 and 2 MeV. The noted improvement in agreement above 2 MeV is almost certainly due to the use by SAI of a revised neutron source term calculated by LANL as an alternate to the ORNL source term. This revised source is somewhat harder than the ORNL version and includes 23% more source neutrons above 3 MeV.

SAI also calculated gamma-ray spectra - comparisons with DREO measurement are shown in Figures 22 through 24. Agreement is generally good at all three ranges shown, with perhaps the best agreement occuring again at the farthest distance of 1080 meters. The gamma-ray peak from thermal neutron capture by hydrogen expected at 2.2 MeV appears instead in the DREO measurements at about 2.1 MeV. This may be evidence of a slight experimental gain-shift downward by some 5% during the 1980 series of measurements. Measurements made in 1981 and 1982 locate this peak instead

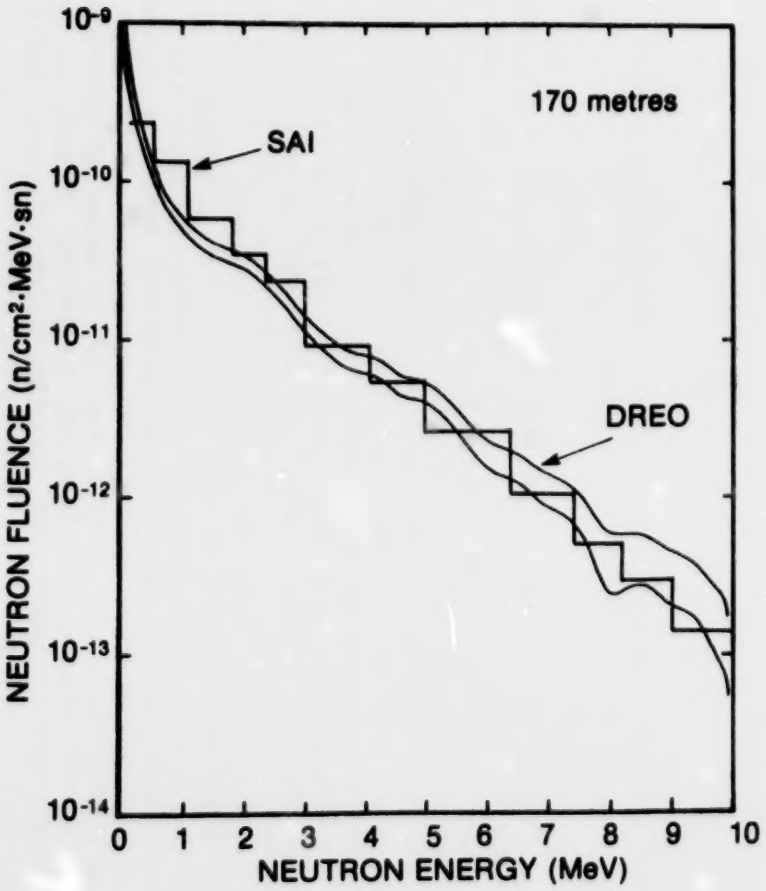

Figure 19 - Comparison of SAI-Calculated and DREO-Measured Neutron Spectra at 170 Meters

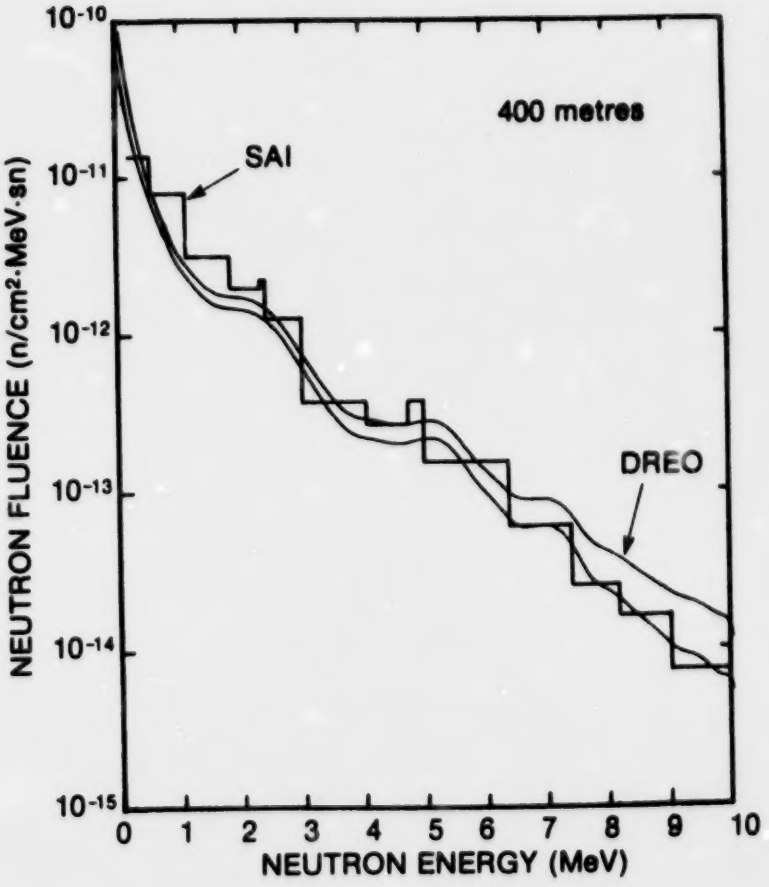

Figure 20 - Comparison of SAI-Calculated and DREO-Measured Neutron Spectra at 400 Meters

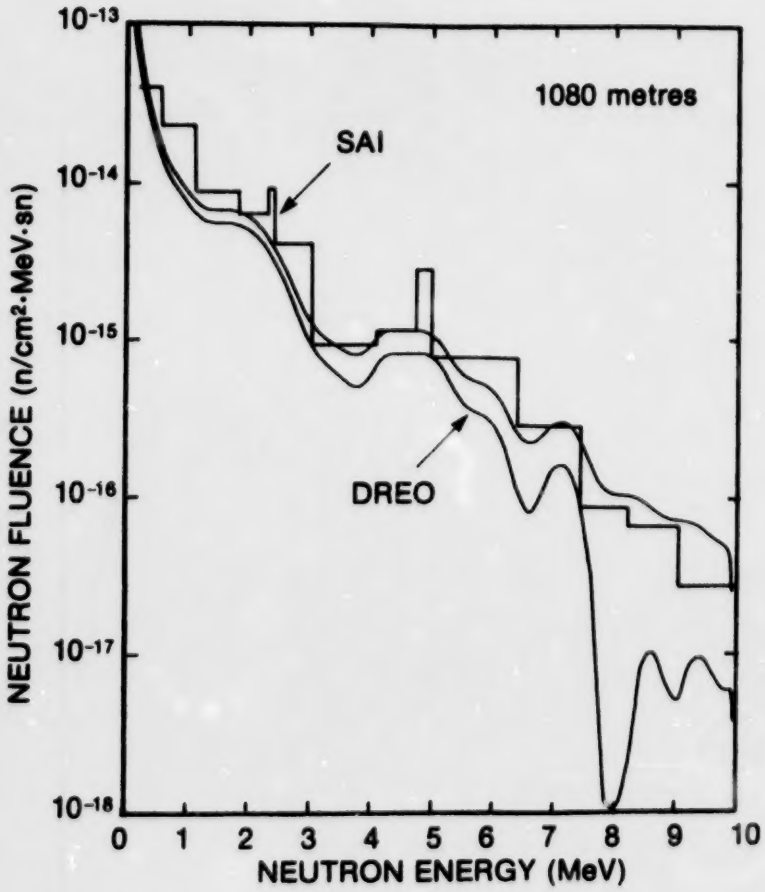

Figure 21 - Comparison of SAI-Calculated and DREO-Measured Neutron Spectra at 1080 Meters

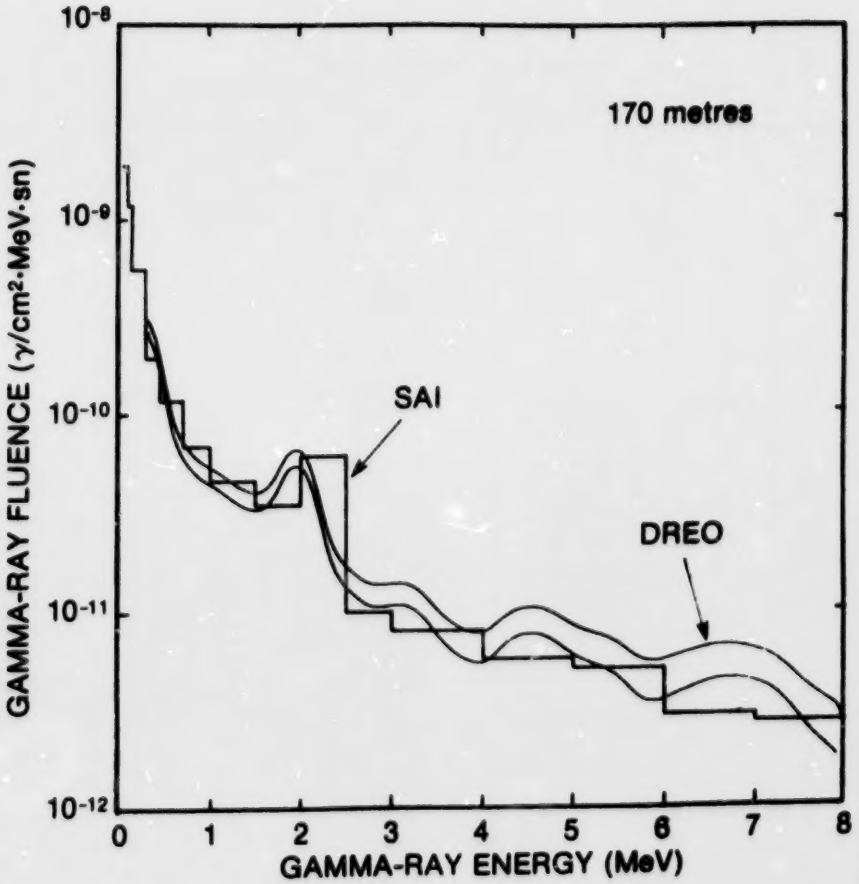

Figure 22 - Comparison of SAI-Calculated and DREO-Measured Gamma-Ray Spectra at 170 Meters

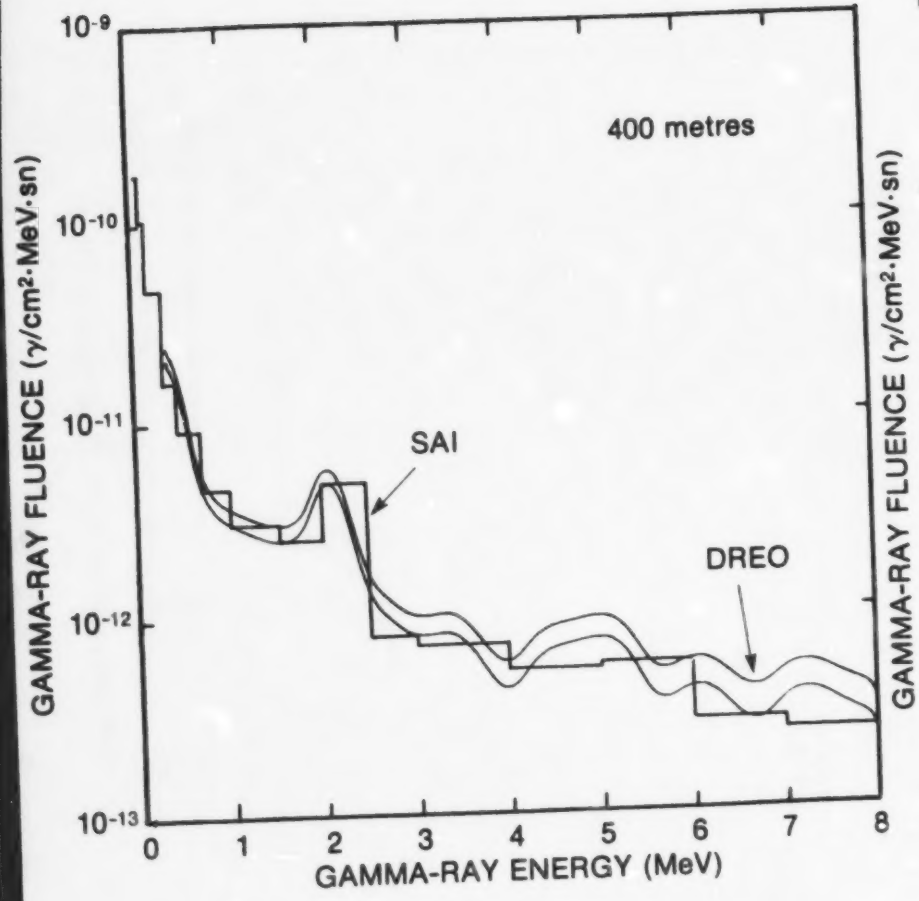

Figure 23 - Comparison of SAI-Calculated and DREO-Measured Gamma-Ray Spectra at 400 Meters

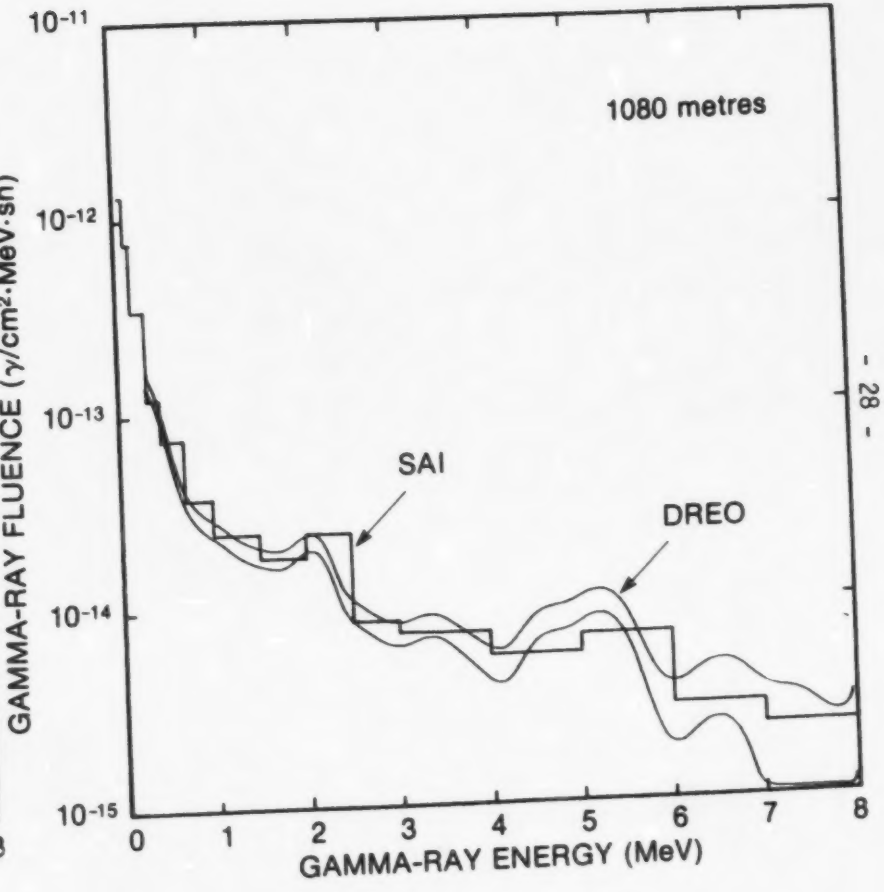

Figure 24 - Comparison of SAI-Calculated and DREO-Measured Gamma-Ray Spectra at 1080 Meters

at the expected energy of 2.2 MeV (see Appendix B), however gamma-ray fluences appear to be unaffected at other energies.

4.4 Comparison to Experimental Dosimetry

In Figure 25 comparisons are shown between calculated integral quantities and the results of corresponding experimental measurement, as functions of ground range. The plotted variables include neutron fluence above 3 MeV and neutron, gamma-ray and total tissue kermas (free-in-air), calculated as ratios of theoretical prediction to the mean of experimental measurements (i.e. with respect to the data of Figures 12 through 15). The calculated data were all scaled using the factor 1.10×10^{17} neutrons per kilowatt-hour (see Appendix H).

Neutron fluences above 3 MeV calculated by ORNL, DREO and LANL are all seen to be lower than the averages of experimental measurement by between 20% and 40%, depending on ground range. All three calculations used the same neutron source description (by ORNL), so the agreement between calculated data is hardly surprising. Experimental measurements at the first three detector locations each included three sulphur determinations by APRD, and one NE-213 determination by each of the three experimental groups, i.e. APRD, WWD and DREO. At 400 meters one APRD sulphur determination is included as is one DREO NE-213 measurement. At 1080 meters the experimental point is the mean of three NE-213 determinations, all by DREO. The observed consistency between experimental measurements is generally better than 10%, so the apparent overprediction by calculations is judged to be of significance. Neutron fluences above 3 MeV are seen to be much better predicted by recent LLNL and SAI calculations, as a result of the use of the newer LANL source term which is significantly harder than the original ORNL version (23% more source neutrons above 3 MeV). Generally these fall within the range of ±25% compared to the mean values of experimental measurement.

Neutron, gamma-ray and total free-in-air tissue kermas are all predicted more accurately by the newer SAI and LLNL calculations than by the older data of ORNL and DREO. Only neutron kermas (and total kermas to the extent of neutron contribution) at 300 and 400 meters differ significantly from experimental quantities. As previously noted it is at these same ranges that the greatest overprediction by calculations of neutron spectra between 0.5 and 2 MeV also occurs, thus the dosimetry confirms to a certain extent the earlier-noted spectral differences. Although conjecture at this point, a possible explanation derives from the fact that between 200 and 450 meters the detectors are located in closest proximity to the forest cover. It is conceivable that the experimental measurements are low due to the partial shielding by the forest, rather than the theoretically-calculated spectra being high for unknown reason. At ranges other than 300 and 400 meters agreement with the latest SAI and LLNL calculations is excellent and unlikely to be further improved, as already the differences are consistent with experimental uncertainty.

4.5 Discussion

Recent LLNL and SAI calculations predict to a high degree of accuracy radiation kermas measured at APRD. Neutron spectra are, however,

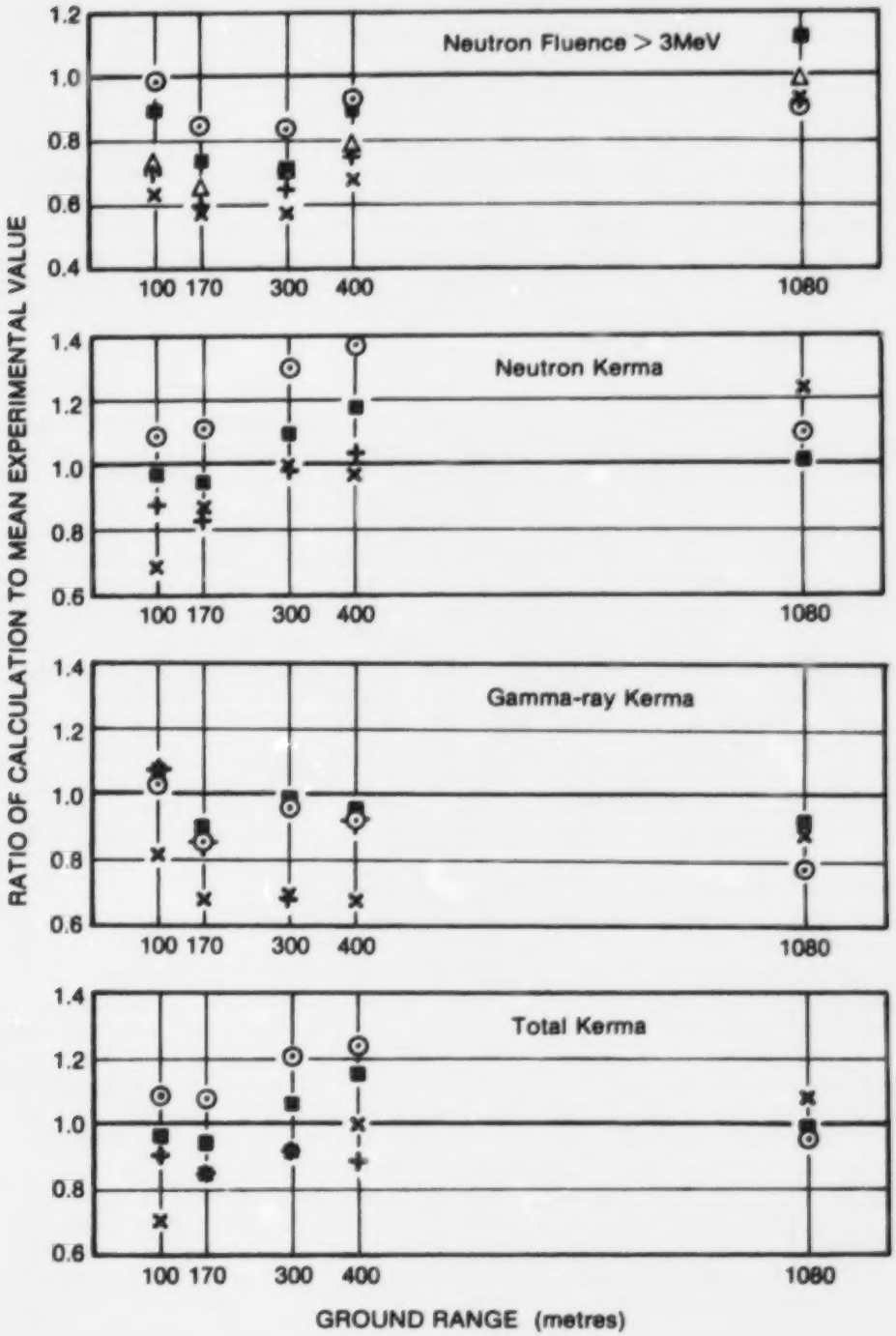

Figure 25 - Comparison of Various Theoretically-Determined Integral Quantities to Those Experimentally Measured
(+ ORNL, x DREO, ■ SAI, ⊙ LLNL, Δ LANL)

overpredicted significantly between 0.5 and 2 MeV (more so when compared to DREO results than either APRD or WWD), and are generally softer than corresponding measurements. Conceivably this disparity may be due either to an inadequacy in the APRD core calculation (and hence neutron leakage spectrum) or to an excessive probability of energy-loss inherent in the scattering cross-section data used in the calculations. Failure of the particle transport methodology by itself is unlikely since both discrete-ordinates and Monte-Carlo calculations are in good agreement with each other. Discrete-ordinates techniques have also been shown to predict measured gamma-ray spectra to a degree of accuracy consistent with experimental uncertainty. Possible spectral biases attributable to experimental techniques are also felt to be an unlikely cause as a result of the demonstrated capabilities to measure very similar neutron spectra from calibrated Cf^{252} sources.

5.0 CONCLUSIONS

Neutron and gamma-ray spectra have been measured at a distance of 1080 meters from the APRD core on three separate occasions, two under prevailing atmospheric conditions which were essentially identical. Good reproducibility of measured spectra was demonstrated, as was the precision of derived integral quantities. Similar measurements performed under conditions of much higher atmospheric temperature and humidity differed only marginally. Recent dosimetric measurements and Bonner-sphere determinations have confirmed the previously-reported experiments employing NE-213 and BF_3 detectors.

Theoretical calculations performed by LANL, SAI and LANL have been found to accurately predict integral quantities of neutron, gamma-ray and total radiation tissue-kerma (free-in-air), although spectral differences between calculations and experiments persist. Calculated neutron spectra are somewhat softer than observation, the most significant differences occuring between 0.5 and 2 MeV where calculations may exceed measurements by as much as 70%. There is some evidence that this discrepancy is greatest at the shorter source-to-detector distances, implying that it may not be the fault of the air-transport component of the theoretical calculation but rather due to an inadequacy in the source term and hence initial core calculation.

Neutron spectra measured on separate occasions by the three experimental groups (APRD, WWD, DREO) differ also in the same energy region of 0.5 to 2 MeV, by up to 40%. The causes of noted experimental inconsistencies are not presently obvious.

To aid in the resolution of these discrepancies, further measurements are suggested:

1. At the next available opportunity APRD, WWD and DREO should simultaneously measure neutron and gamma-ray spectra from the APRD Cf^{252} source, under identical experimental conditions. Comparison of unfolded spectra will then indicate whether noted experimental differences are traceable to the different measurement

and analysis techniques employed by the three groups, or instead merely due to the uncontrollable vagaries of NE-213 spectroscopy.

2. The validity of comparison between theoretical calculation and experimental measurement might be improved if more accurate determinations of the spectral and directional characteristics of core leakage were available. Ideally the same detectors should be employed as previously used in air-transport measurements, however high dead-time effects preclude their location at small source-to-detector separations. Possibly smaller NE-213 scintillators might be employed instead with lower efficiencies. In any event, determinations should be made after a substantial core-cooling period and at several polar angles and source-to-detector separations. The measured spectra may then be used as source terms in subsequent air-transport calculations, thus avoiding the current reliance on core-calculations of source leakage.

3. Future investigations should also address the noted spectral discrepancies between neutron energies of 0.5 and 2 MeV. An effort to improve experimental accuracy should be made, possibly utilizing high-pressure He^3 spectrometers and/or activation methods as well as attempting to lower the present threshold of 600 KeV attributable to the NE-213 scintillators.

4. An experimental program initiated recently by the Etablissement Technique Central de l'Armament (France) to measure angular distributions of air-transported spectra at APRD should also be pursued as such information will provide a verification of the adaquacy of theoretical calculations not only in energy but also particle direction.

6.0 ACKNOWLEDGEMENTS

The authors are greatly indebted to the staff of the US Army Pulsed Radiation Division, in particular A.H. Kazi, C.R. Heimbach and R.C. Harrison; to D.L. Rigotti and A.E. Rainis of the Ballistics Research Laboratory and to C.N. Davidson of the US Army Nuclear and Chemical Agency for their considerable assistance in planning, performing and analysing the measurements reported herein and for their many helpful suggestions and discussions over the past few years.

7.0 REFERENCES

[1] A.H. Kazi, C.R. Heimbach, R.C. Harrison (APRD) and L. Schänzler, F.W. Buchholz (WWD), "Measurements of the Free-Field Radiation Environment at the APRD Reactor", Aberdeen Proving Ground Report APG-MT-5279 (July 1979), Aberdeen Proving Ground, Maryland, USA.

[2] L. Schänzler, F.W. Buchholz (WWD) and A.H. Kazi, C.R. Heimbach, R.C. Harrison (APRD), "Measurement of the Free-Field Radiation Environment at the APRD Reactor", WWD Report No. 27, (Feb. 1979).

[3] H.A. Robitaille, and B.E. Hoffarth, "A Comparison of Measured and Calculated Air-Transported Radiation from a Fast, Unshielded Nuclear Reactor", Defence Research Establishment Ottawa Report DREO R-835 (Dec. 1980).

[4] A.H. Kazi, C.R. Heimbach and R.C. Harrison, "Neutron and Gamma Radiation Measurements and Calculations up to 1.1 Kilometers from a Fission Source", Aberdeen Proving Ground Report APG-MT-5490 (Jan. 1981).

[5] H.A. Robitaille, A.H. Kazi, C.R. Heimbach and R.C. Harrison, "Measurement and Calculation of Radiation Transport to 1.1 Km from a Fission Source", Transactions of the American Nuclear Society, 39, 772 (1981).

[6] A.H. Kazi, C.R. Heimbach, L. Schänzler, J.V. Pace III and A.E. Rainis, "Comparison of Experimental Radiation Transport with Calculation", Transactions of the American Nuclear Society, 33, 706 (1979).

[7] V.P. Bond, and J.W. Thiessen (Eds.), "Reevaluation of Dosimetric Factors : Hiroshima and Nagasaki", US Department of Energy Symposium Series 55, CONF-810928 (1982).

[8] C.R. Heimbach, "Bonner Sphere Measurements of the APRD Free-Field Neutron Environment", Aberdeen Proving Ground Report APG-MT-5682, (July 1982).

[9] C.R. Heimbach, "Effect of Weather on Neutron Spectrum at 1080 m Range Using Bonner Sphere Spectrometer", Aberdeen Proving Ground Memo for Record STEAP-MT-R 11-82, (24 July 1982).

[10] A.H. Kazi, R.C. Harrison and C.R. Heimbach, "Radiation Dose Measurements at 1.6 km Range - Preliminary Data Analysis", Aberdeen Proving Ground Memo for Record STEAP-MT-R 17-82, (27 August 1982 - revised).

[11] C.R. Heimbach, "Bonner Sphere Measurements at 1.6 km", Aberdeen Proving Ground Memo for Record STEAP-MT-R 16-82, (16 August 1982).

[12] W.E. Loewe, W.A. Turin, C.W. Pollock, A.C. Springer and B.L. Richardson, "Validated Deep-Penetration, Air-Over-Ground Neutron-Gamma Transport", Lawrence Livermore National Laboratory Report UCRL-88498 (April 1982).

[13] Private Communication; D.C. Kaul, SAI, 7 June 1982.

[14] G.P. Estes, R.C. Little, R.E. Seamon and P.D. Soran, "Air Transport in Connection with the Hiroshima-Nagasaki Dose Reevaluation Effort", Los Alamos National Laboratory Report LA-9369-M5, (July 1982).

[15] A.H. Kazi, "Fast-Pulse Reactor Operation with Reflector Control and a 106-mm-diam Glory Hole", Nuclear Science and Engineering, 60, 62-73, (1976).

[16] E.D. McGarry, A.H. Kazi, G.S. Davis and D.M. Gilliam, "Absolute Neutron-Flux Measurements at Fast-Pulse Reactors with Calibration Against Californium-252", IEEE Transactions on Nuclear Science, NS-23, 6, 2002, (Dec. 1976).

[17] A.H. Kazi, D.R. Harrell, E.J. Kaufman and W.S. Eaton, "Measurement of APRD Reactor > 3 MeV Fluence Source Distribution", Aberdeen Proving Ground Memo for Record STEAP-MT-R 8-82, (17 May 1982).

[18] R.C. Little, "Calculation of APRD Reactor", LANL Memorandum to P.P. Whalen, (21 Jan. 1982).

[19] Private Communication; P.P. Whalen, LANL, (July 1982).

[20] W.R. Burres, and R.M. Freestone, Jr., "FERDOR, A Simple and Honest Unfolding Code", Oak Ridge National Laboratory Report ORNL-TM-2709, (1969).

[21] V.V. Verbinski, W.R. Burres, T.A. Love, W. Zobel, N.W. Hill and R. Textor, "Calibration of an Organic Scintillator for Neutron Spectroscopy", Nuclear Instruments and Methods, 65, 8-25, (1968).

[22] F.W. Buchholz, L. Schänzler, S. Stüker, G. Tumbrägel and M. Weinert, "Californium Liquid Air Tank Experiment", WWD Report Nr 33, (Dec. 1976).

[23] N.A. Lurie, L. Harris and J.C. Young, "Calculation of Gamma-ray Response Matrix for 5-cm NE-213 Organic Liquid Scintillation Detectors", Nuclear Instruments and Methods, 129, 543-555, (1975).

[24] H.A. Robitaille, "Rapid, On-Line Matrix Unfolding of Fast-Neutron Spectroscopic Data from Organic Scintillators", Third Symposium on Neutron Dosimetry in Biology and Medicine, Neuherberg/Munchen, (May, 1977), EUR-5848, Commission of the European Communities.

[25] F.P. Szabo, "A Fast-Neutron Spectrometer", Defence Research Establishment Ottawa Report R-637, (July, 1971).

[26] R.E. Textor, and V.V. Verbinski, "05S, A Monte-Carlo Code for Calculating Pulse Height Distributions due to Monoenergetic Neutrons Incident on Organic Scintillators", Oak Ridge National Laboratory Report ORNL 4168, (1968).

[27] K.G. Harrison, and P.M. Thomas, "Multisphere Neutron Spectroscopy and Dosimetry", Fourth Symposium on Neutron Dosimetry in Biology and Medicine, Neuherberg/Munchen, (June, 1981), EUR-7448 (Vol. II), Commission of the European Communities.

[28] J.J. Broerse, G. Burger and M. Coppola (Eds), "A European Neutron Dosimetry Intercomparison Project (ENDIP) Results and Evaluation", Commission of the European Communities, EUR-6004, (1978).

[29] W.A. Rhodes, and F.R. Mynatt, "The DOT-III Two-Dimensional Discrete Ordinates Transport Code", Oak Ridge National Laboratory Report TM-4280, (June 1973).

[30] D.E. Bartine, J.R. Knight, J.V. Pace III and R.W. Roussin, "Production and Testing of the DNA Few-Group Cross Section Library", Oak Ridge National Laboratory Report TM-4840, (Oct. 1975).

[31] P.P. Whalen, "Status of Los Alamos Efforts Related to Hiroshima and Nagasaki Dose Estimates", US Department of Energy Sumposium Series 55, CONF-810928 (1982).

[32] W.W. Engle, Jr., "ANISN, A One-Dimensional Discrete-Ordinates Transport Code with Anisotropic Scattering", Oak Ridge National Laboratory Report K-1693, (March 1967).

APPENDIX A
PLOTTED FREE-FIELD NEUTRON SPECTRA MEASURED AT APRD

APPENDIX A: PLOTTED FREE-FIELD NEUTRON SPECTRA MEASURED AT APRD

Neutron spectra obtained experimentally at APRD by DREO during the period 1980 to 1982 inclusive are shown plotted semi-logarithmically on the following pages. Only those data recorded by the NE-213 spectrometer are shown, in particular neutrons between 600 KeV and 10 MeV. Three curves are shown on each graph; a central curve corresponding to the best estimate of the neutron fluence and two others indicating the range within which there is a 68% probability (± one standard deviation) of finding the actual neutron spectrum, as estimated by DREO unfolding techniques. Note that this uncertainty does not reflect the possible error attributable to reactor power reproducibility, currently estimated to be ± 2%.

Conditions under which these spectra were obtained are tabulated below:

FIGURE	RANGE (meters)	YEAR	TEMPERATURE (°C)	PRESSURE (mBar)	HUMIDITY (% RH)	AIR DENSITY (g/litre)
A-1	15	1980	17	1025	43	1.225
A-2	100	1980	13	1021	78	1.236
A-3	170	1980	13	1021	78	1.236
A-4	179	1981	14	1032	58	1.234
A-5	260	1981	15	1022	58	1.232
A-6	300	1980	13	1021	78	1.236
A-7	400	1980	10	1025	50	1.260
A-8	1080	1980	16	1023	62	1.228
A-9	1080	1981	13	1011	58	1.229
A-10	1080	1982	29	1015	74	1.157

All measurements were made with the reactor operating outdoors and at its maximum height of fourteen meters; with the exceptions of A-1 for which both core and detector heights were 5.34 meters, and A-4 and A-5 during which the reactor was located inside and at the centre of its aluminum silo, at a height of fourteen meters.

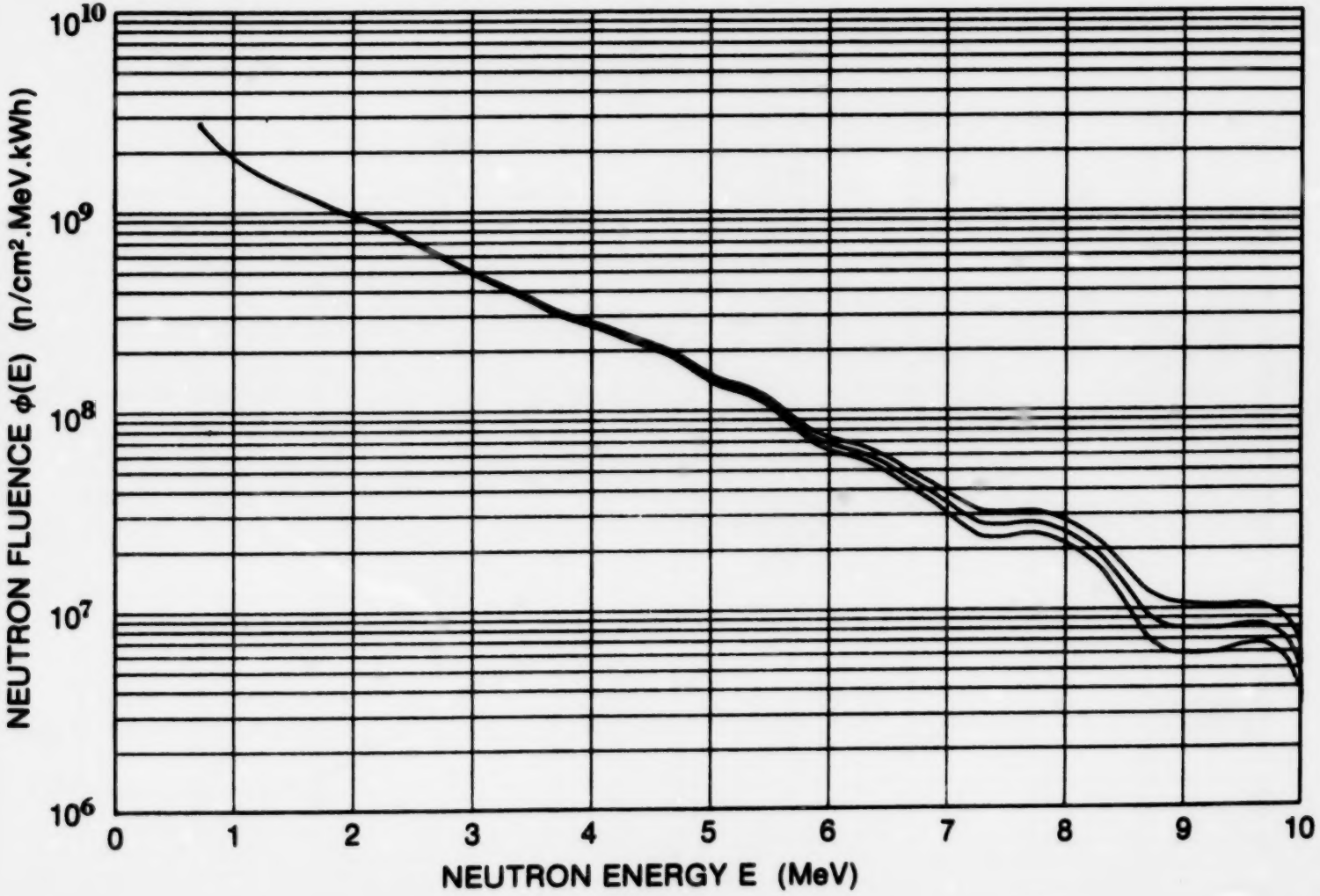

Figure A-1: Free-Field Neutron Spectrum Obtained at a Range of 15 Meters (1980)

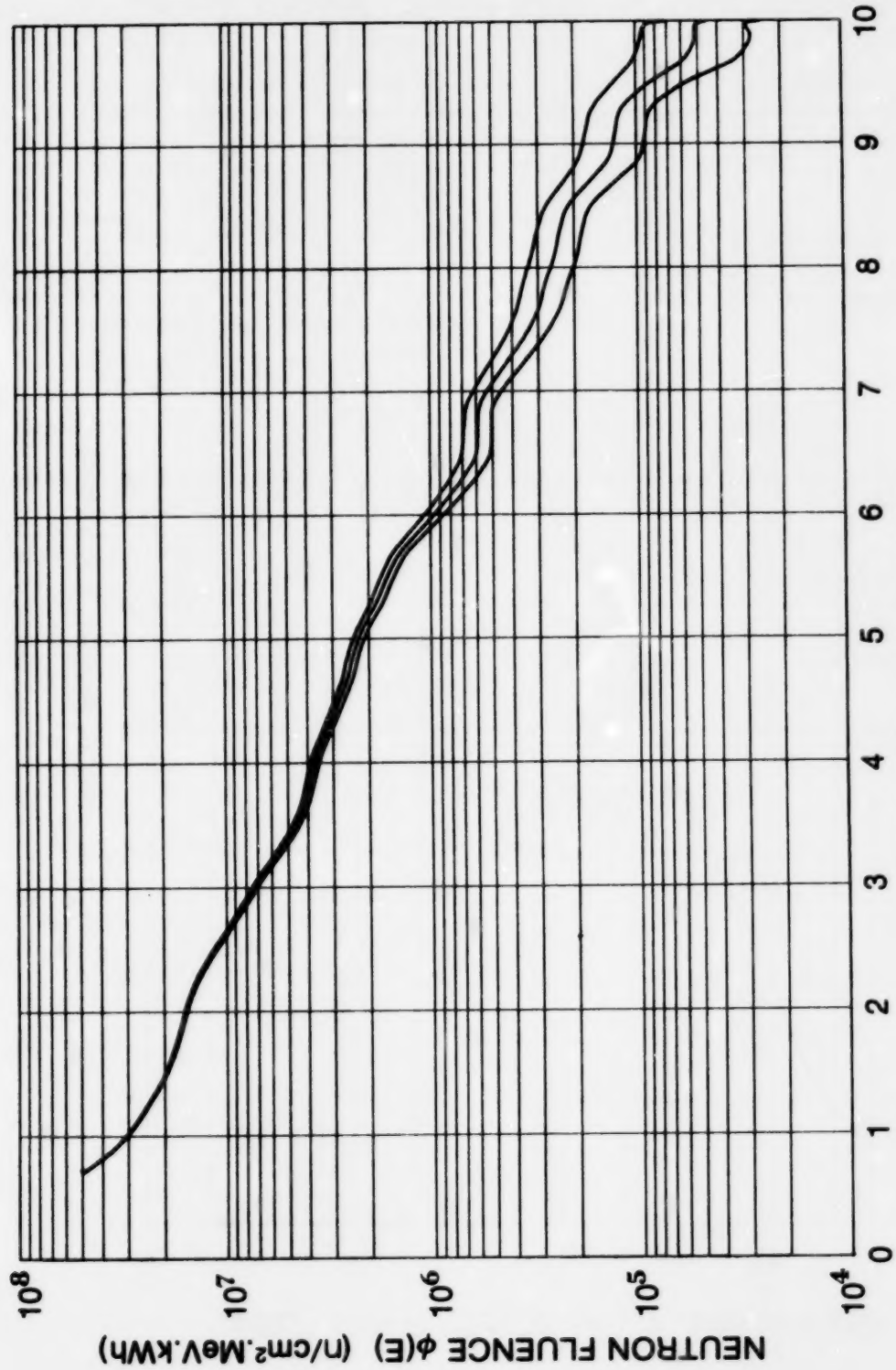

Figure A-2: Free-Field Neutron Spectrum Obtained at a Range of 100 Meters (1980)

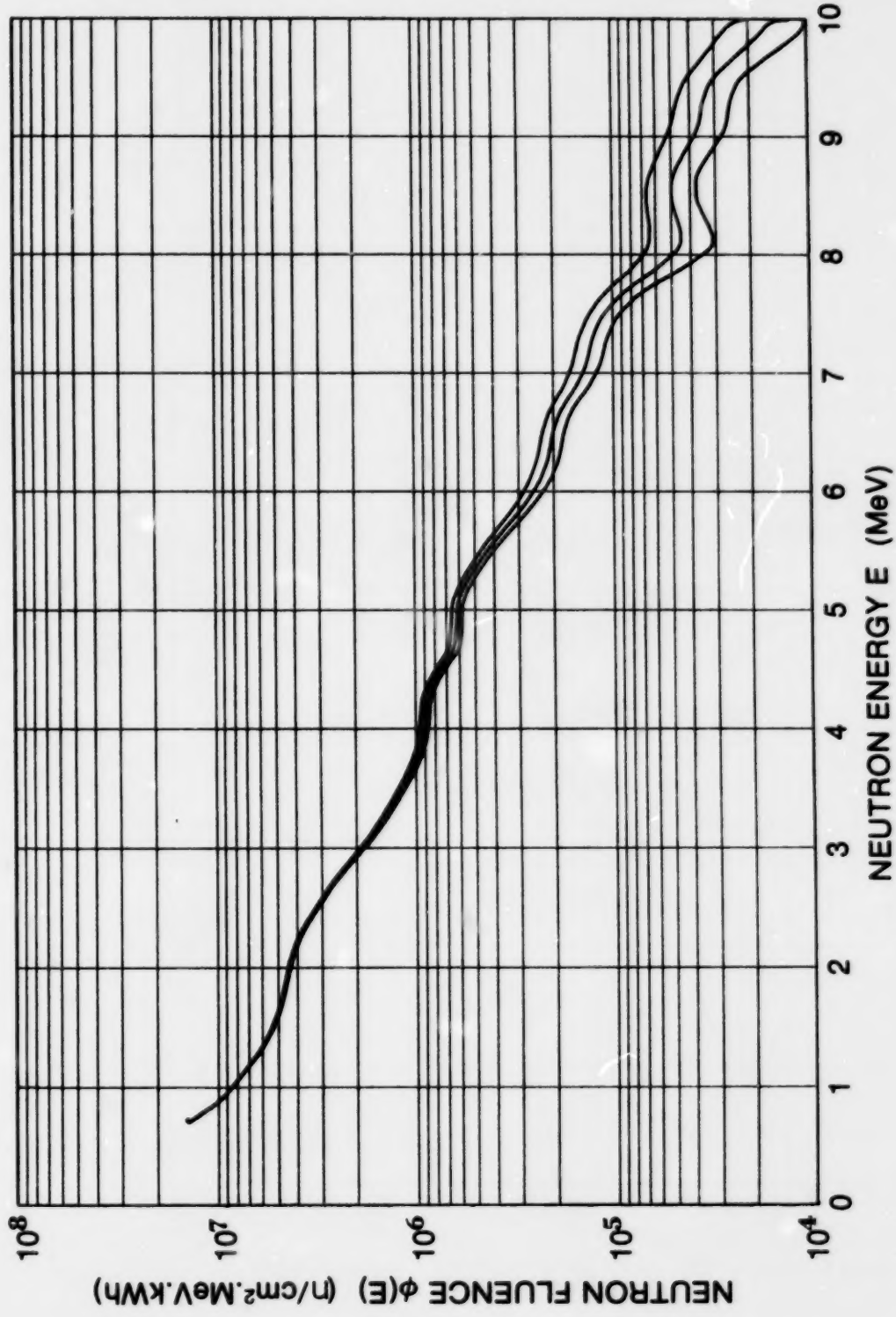

Figure A-3: Free-Field Neutron Spectrum Obtained at a Range of 170 Meters (1980)

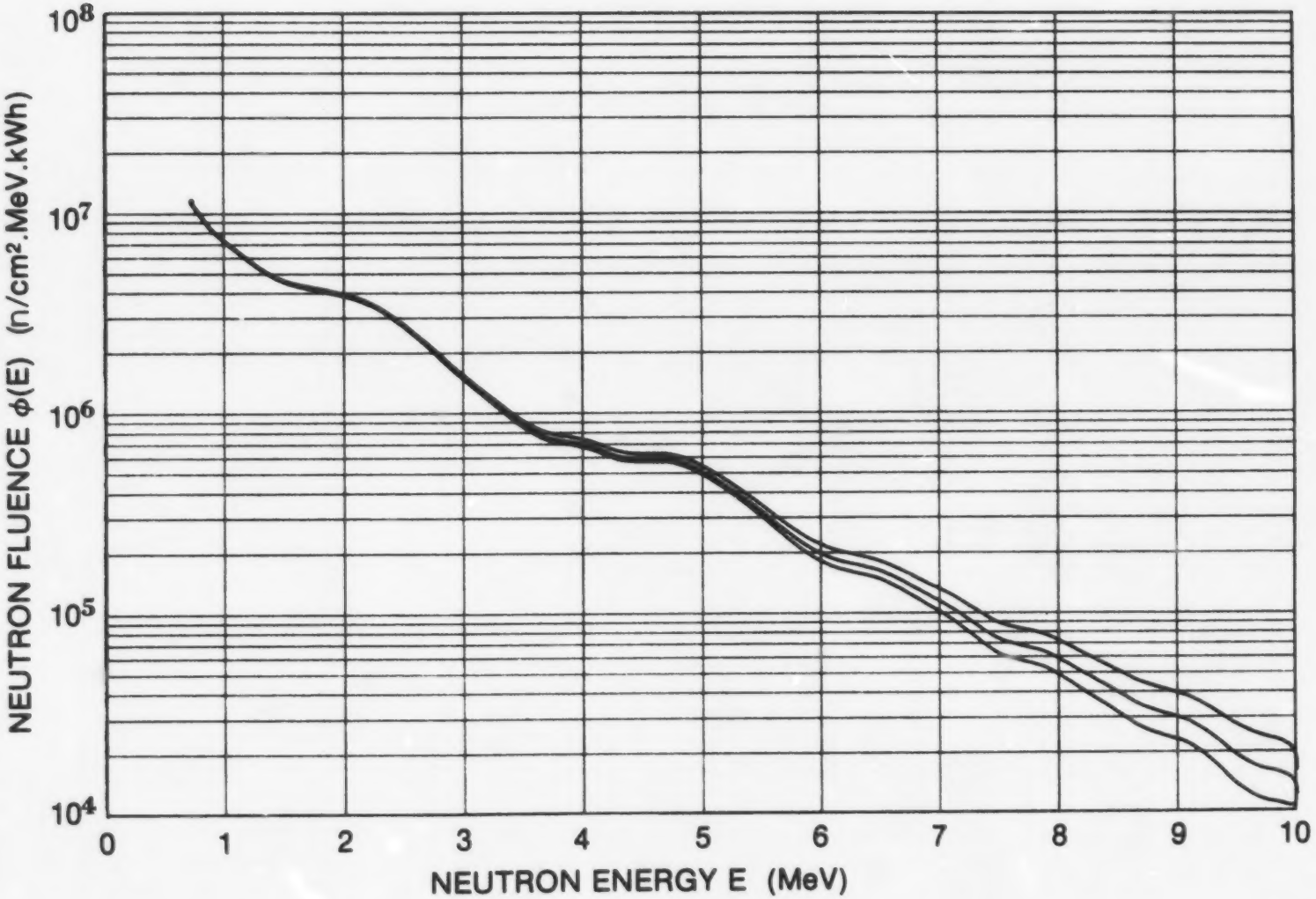

Figure A-4: Free-Field Neutron Spectrum Obtained at a Range of 179 Meters (1981)

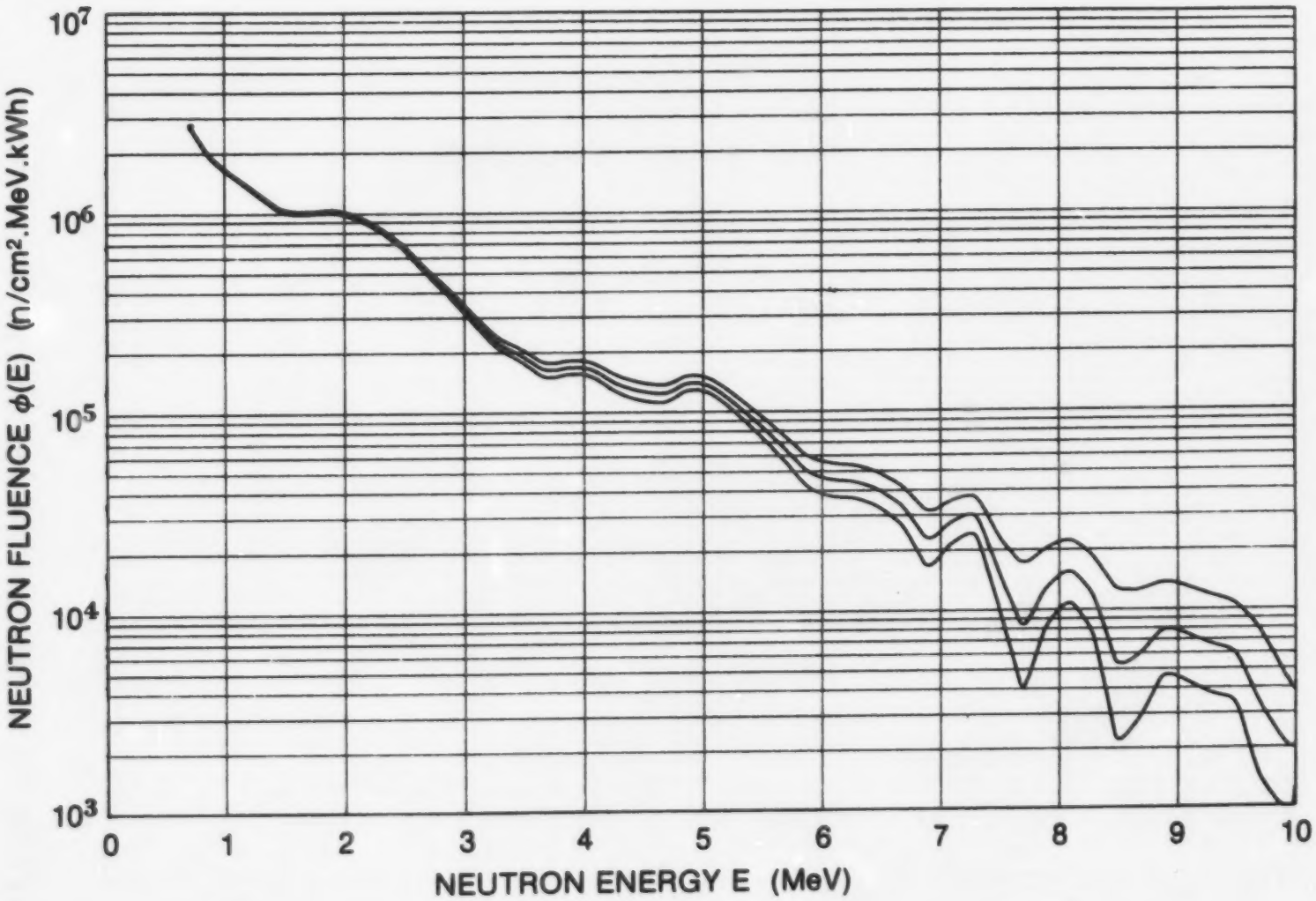

Figure A-5: Free-Field Neutron Spectrum Obtained at a Range of 260 Meters (1981)

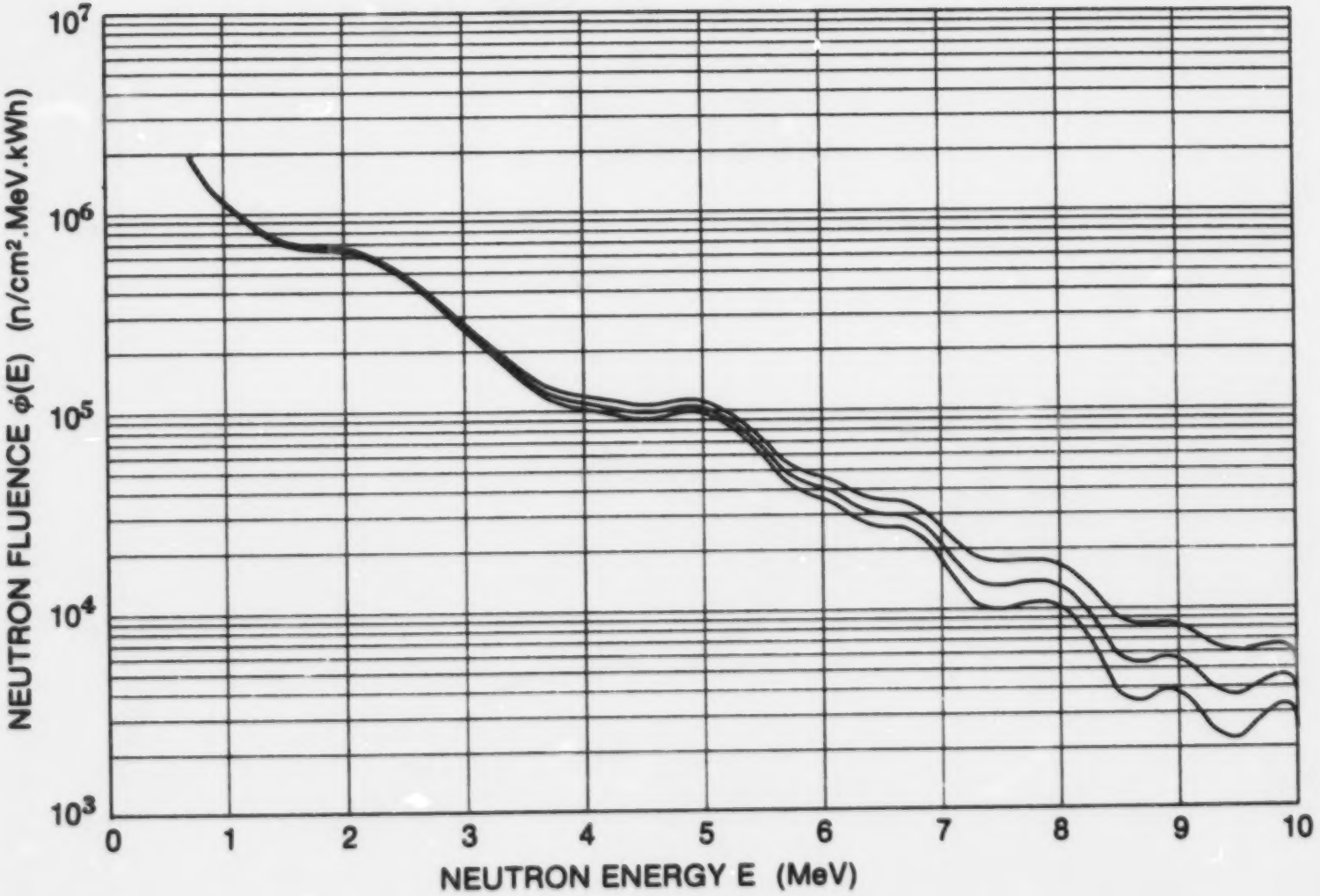

Figure A-6: Free-Field Neutron Spectrum Obtained at a Range of 300 Meters (1980)

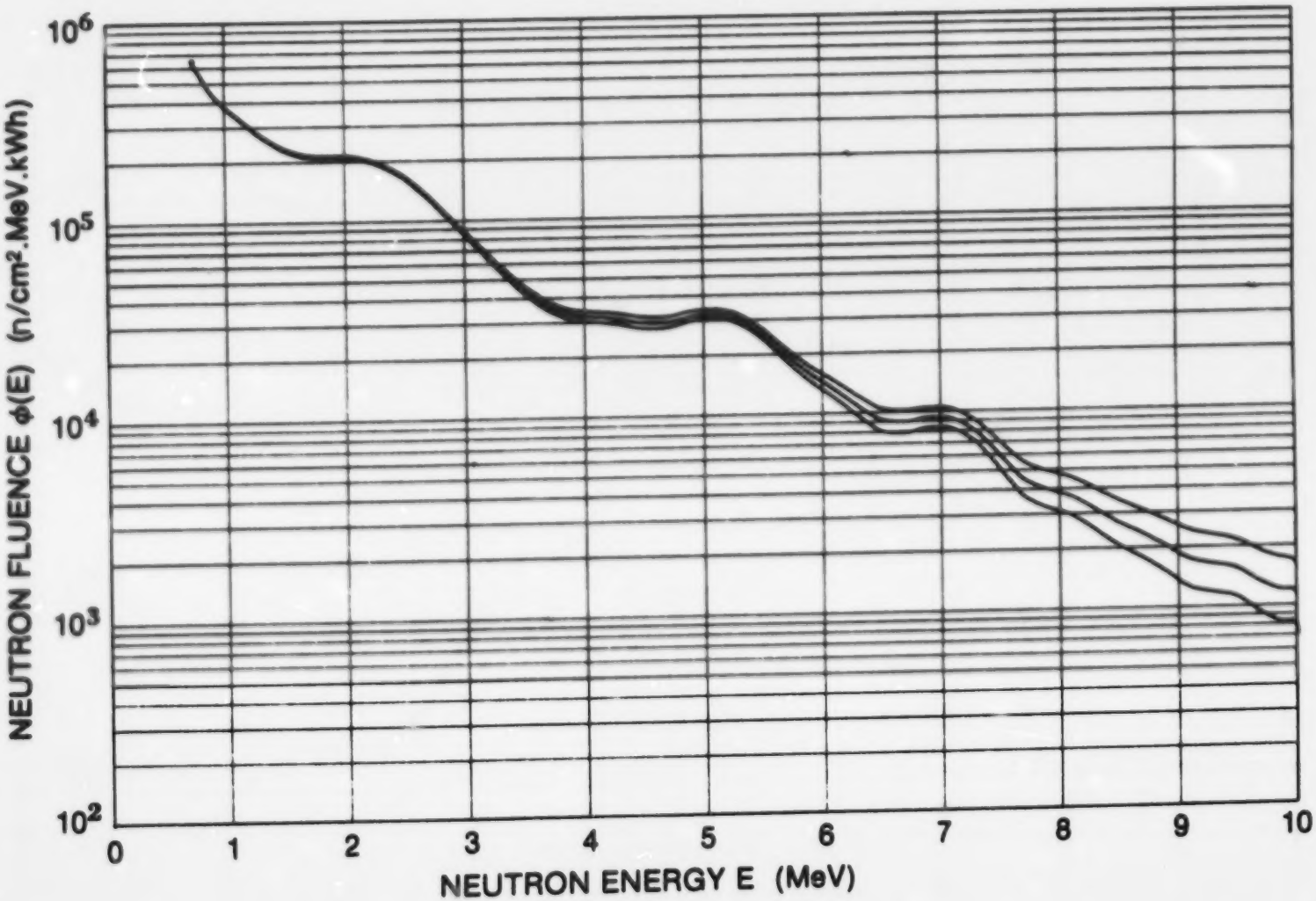

Figure A-7: Free-Field Neutron Spectrum Obtained at a Range of 400 Meters (1980)

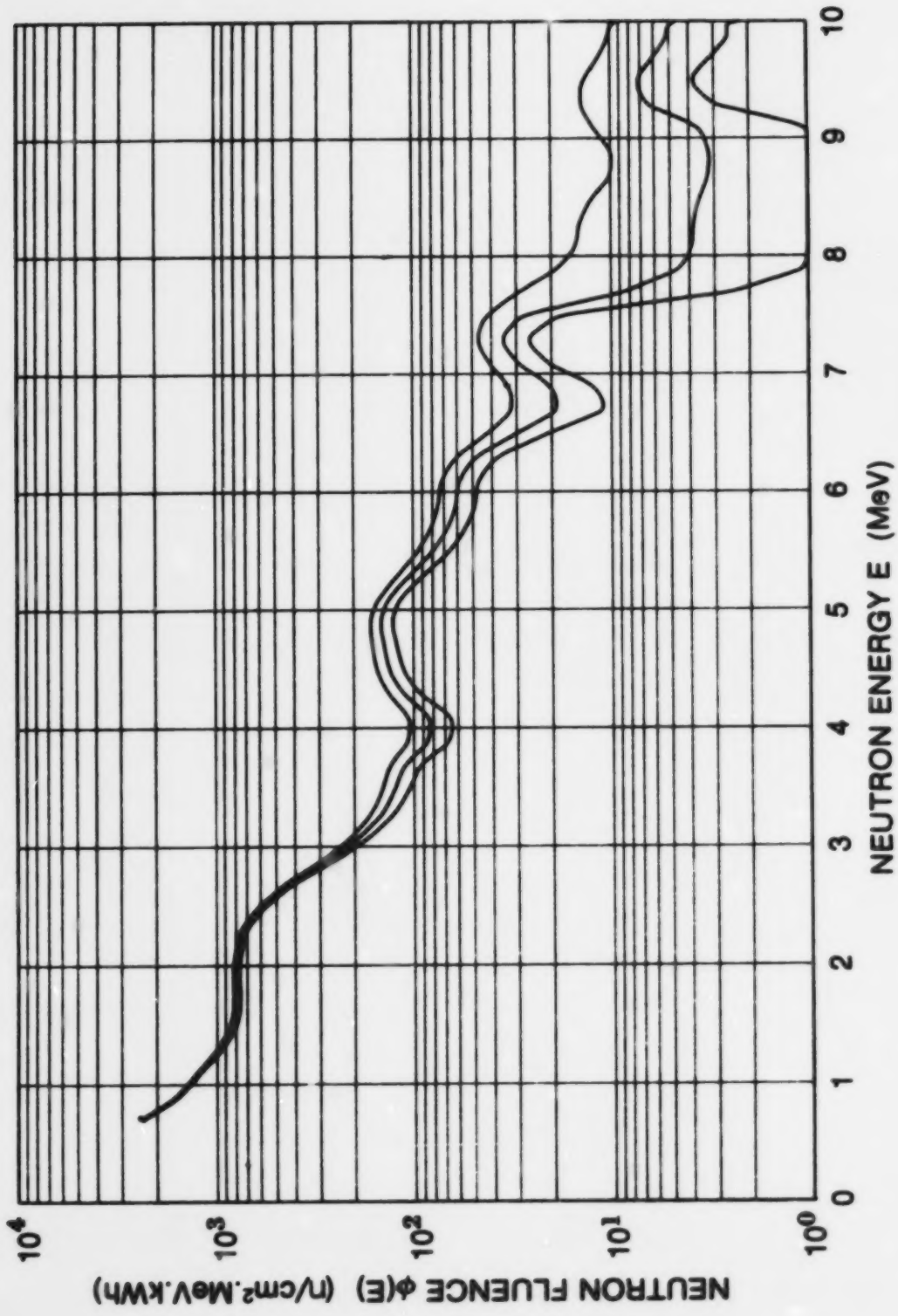

Figure A-8: Free-Field Neutron Spectrum Obtained at a Range of 1080 Meters (1980)

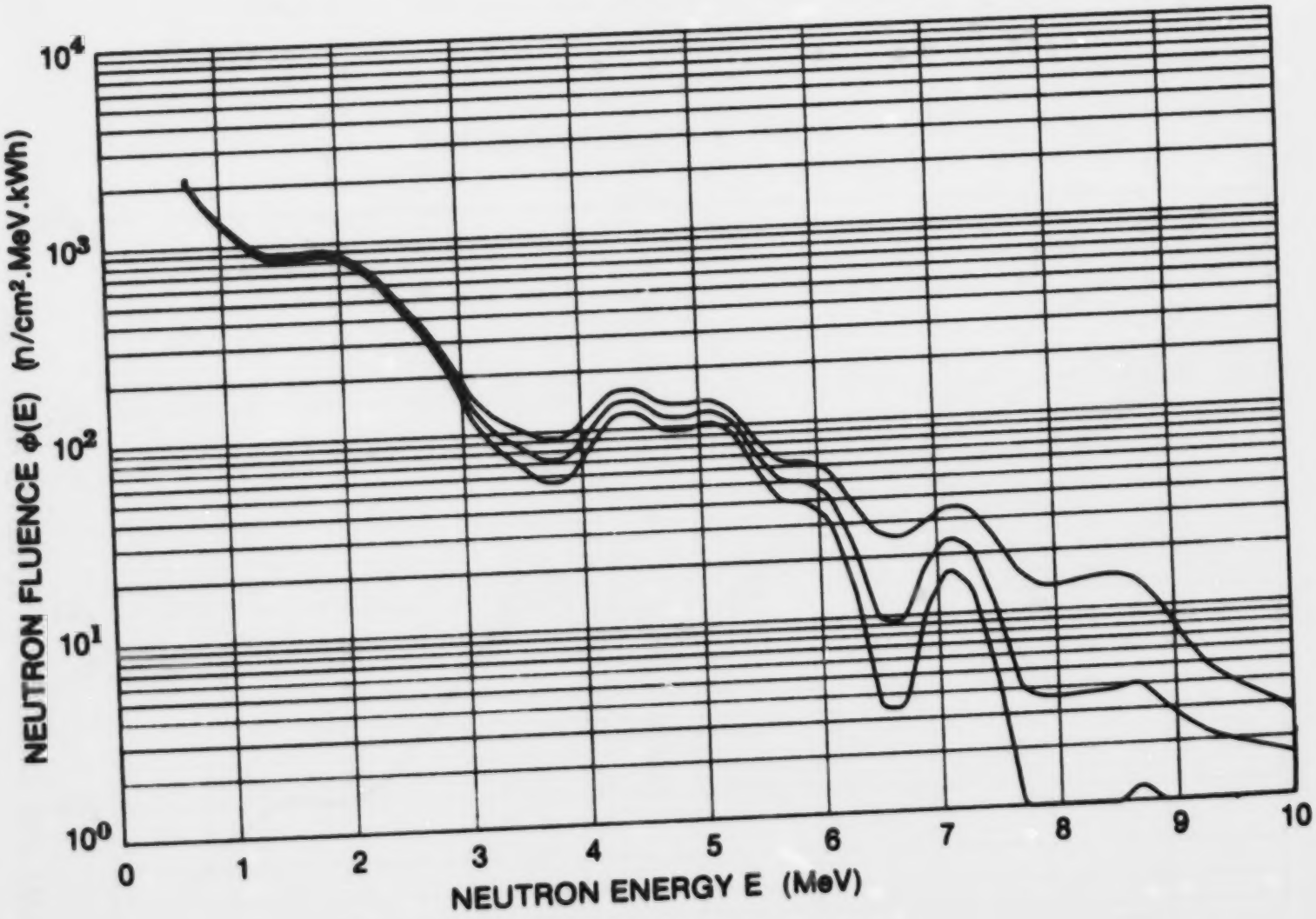

Figure A-9: Free-Field Neutron Spectrum Obtained at a Range of 1080 Meters (1981)

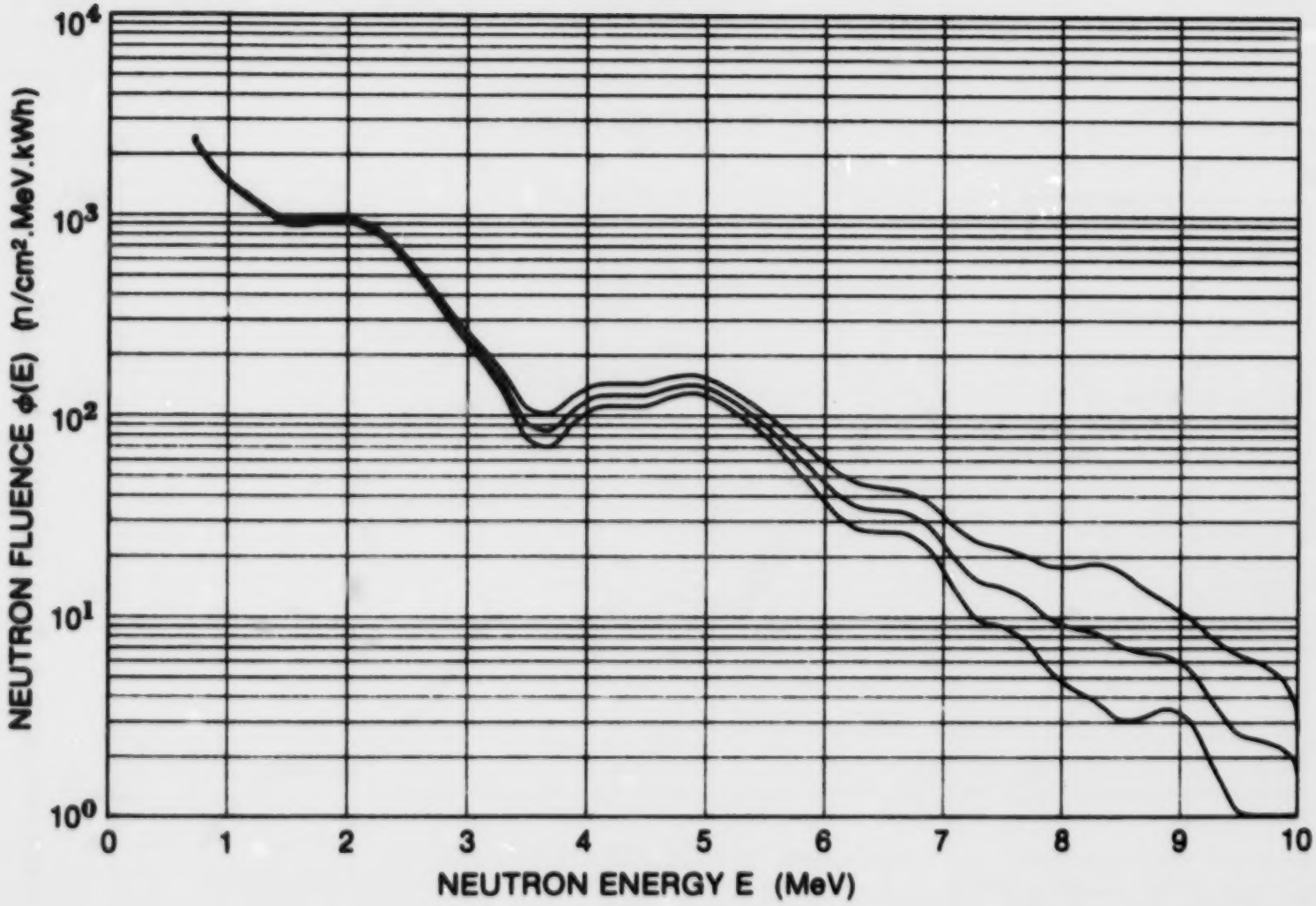

Figure A-10: Free-Field Neutron Spectrum Obtained at a Range of 1080 Meters, Under Conditions of High Temperature and Relative Humidity (1982)

APPENDIX B
PLOTTED FREE-FIELD GAMMA-RAY SPECTRA MEASURED AT APRD

APPENDIX B: PLOTTED FREE-FIELD GAMMA-RAY SPECTRA MEASURED AT APRD

Gamma-ray spectra obtained experimentally at APRD by DREO during the period 1980 to 1982 inclusive are shown plotted on the following pages. The comments of Appendix A (q.v.) apply equally to the measured gamma-ray spectra, with two exceptions. At a range of fifteen meters gamma-ray determinations were impossible due to an excessive background resulting from the fission product inventory of the core, consequently no Figure B-1 is shown. In order to be consistent with Appendix A the data are thus numbered sequentially from B-2. As in Appendix A only NE-213 determinations are shown, however with a different energy range, namely 300 KeV to 8 MeV.

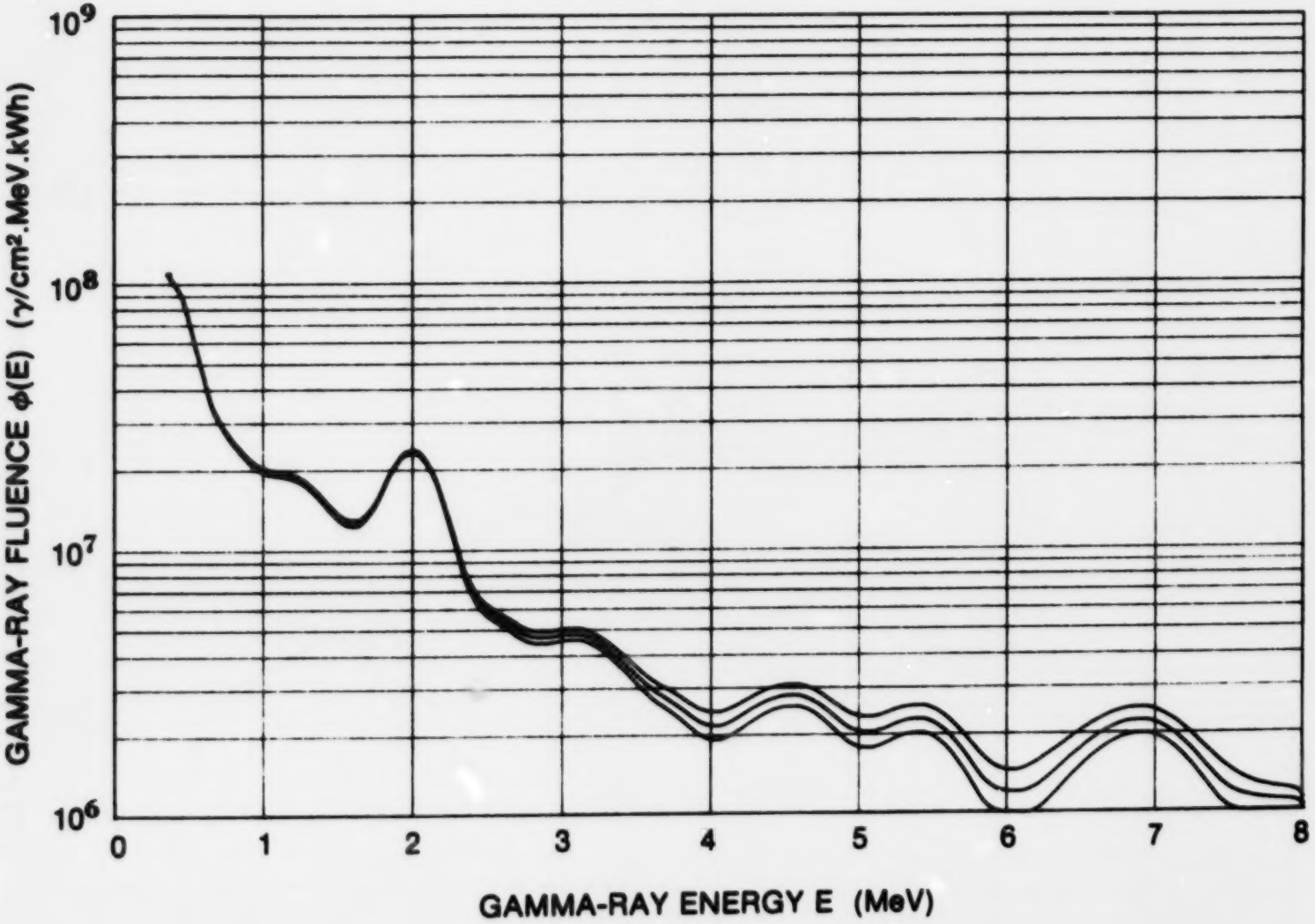

Figure B-2: Free-Field Gamma-Ray Spectrum Obtained at a Range of 100 Meters (1980)

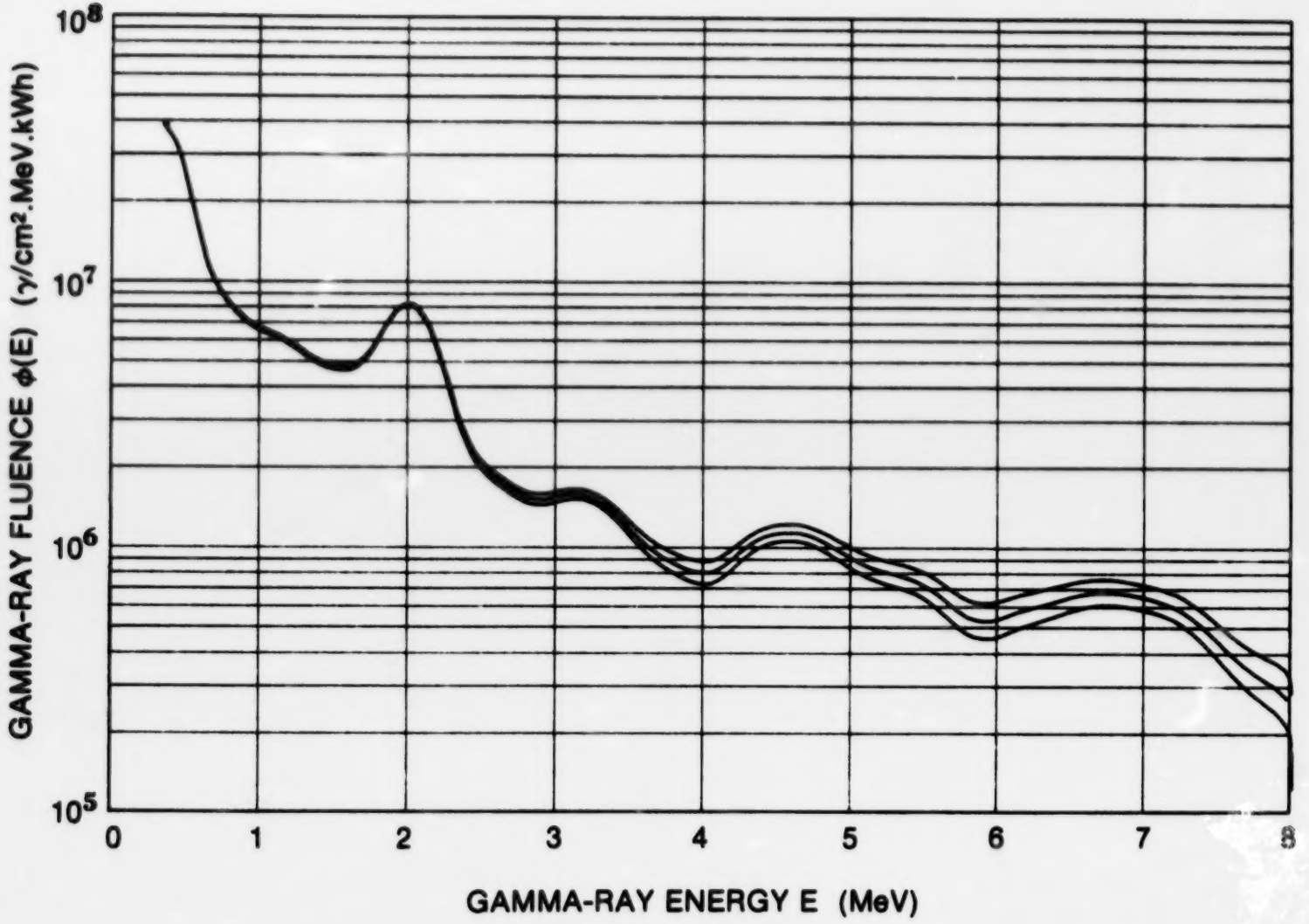

Figure B-3: Free-Field Gamma-Ray Spectrum Obtained at a Range of 170 Meters (1980)

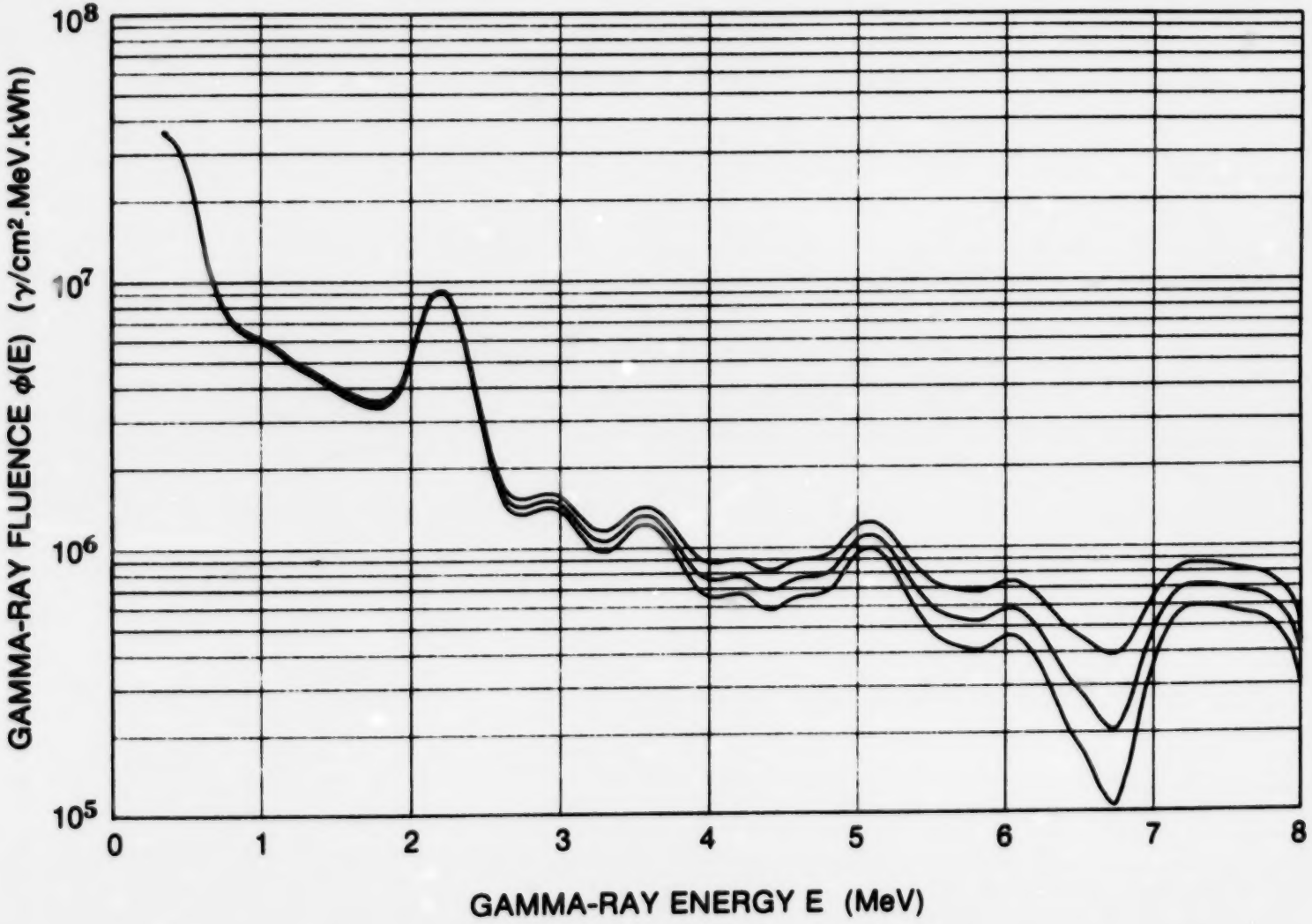

Figure B-4: Free-Field Gamma-Ray Spectrum Obtained at a Range of 179 Meters (1981)

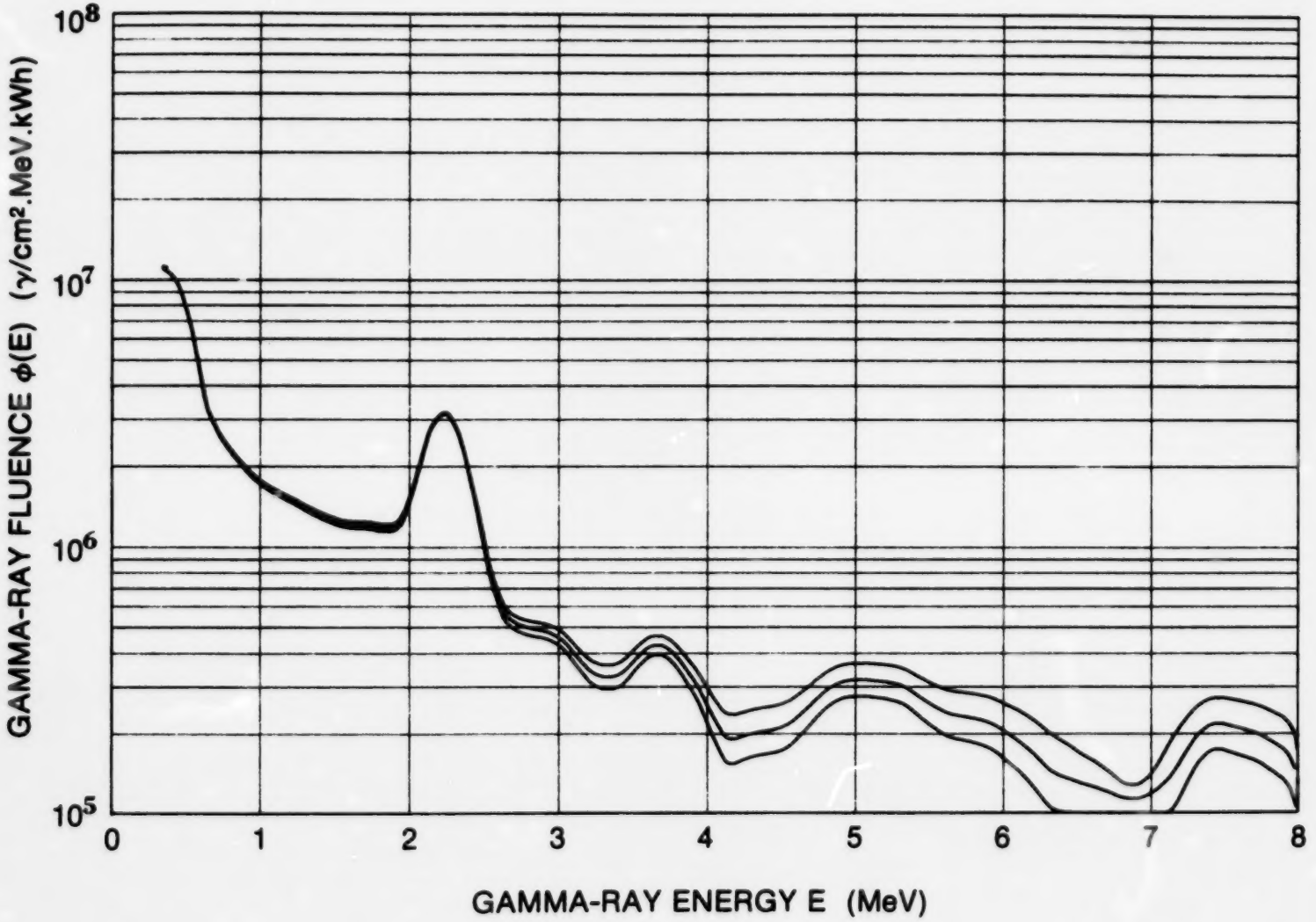

Figure B-5: Free-Field Gamma-Ray Spectrum Obtained at a Range of 260 Meters (1981)

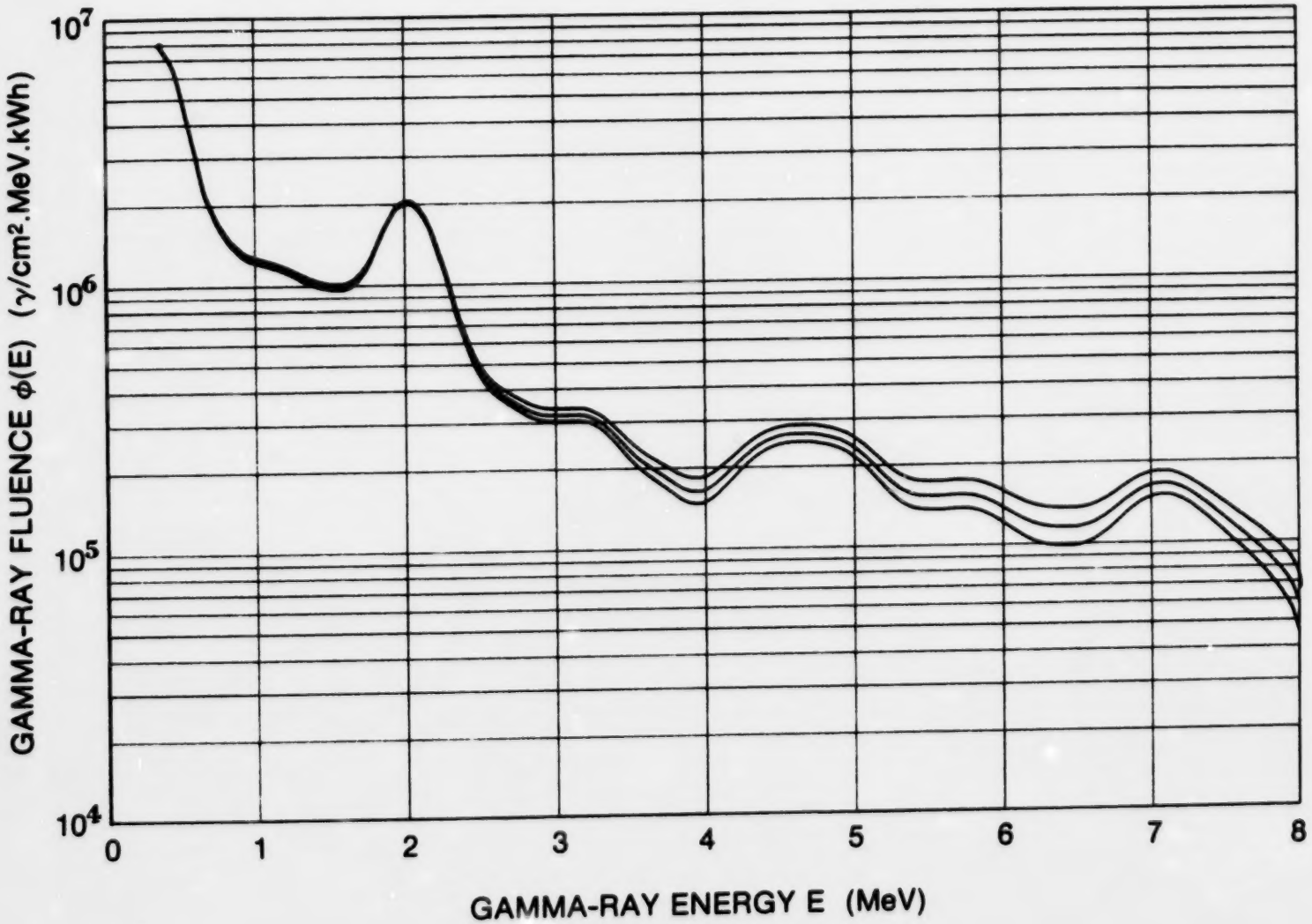

Figure B-6: Free-Field Gamma-Ray Spectrum Obtained at a Range of 300 Meters (1980)

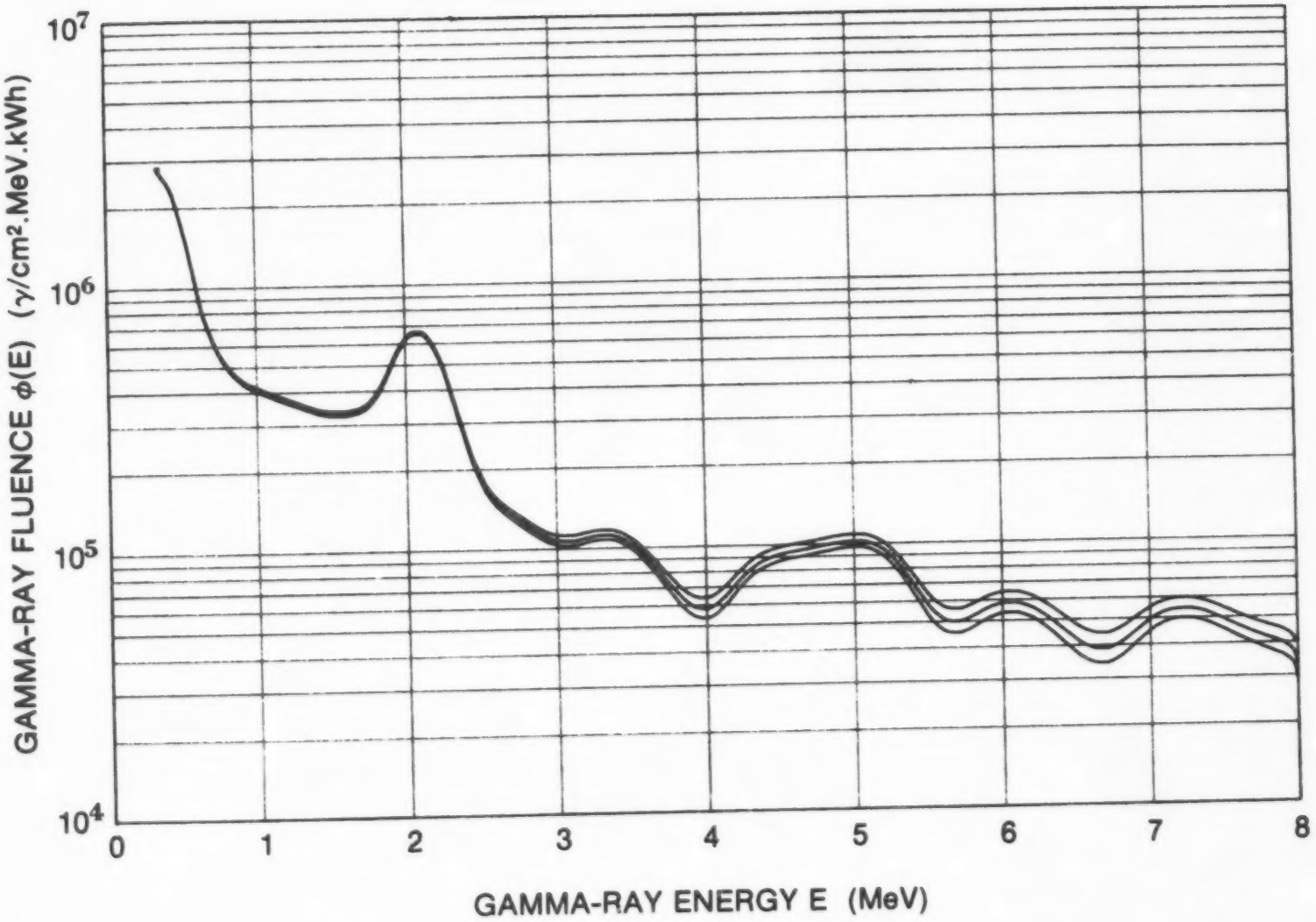

Figure B-7: Free-Field Gamma-Ray Spectrum Obtained at a Range of 400 Meters (1980)

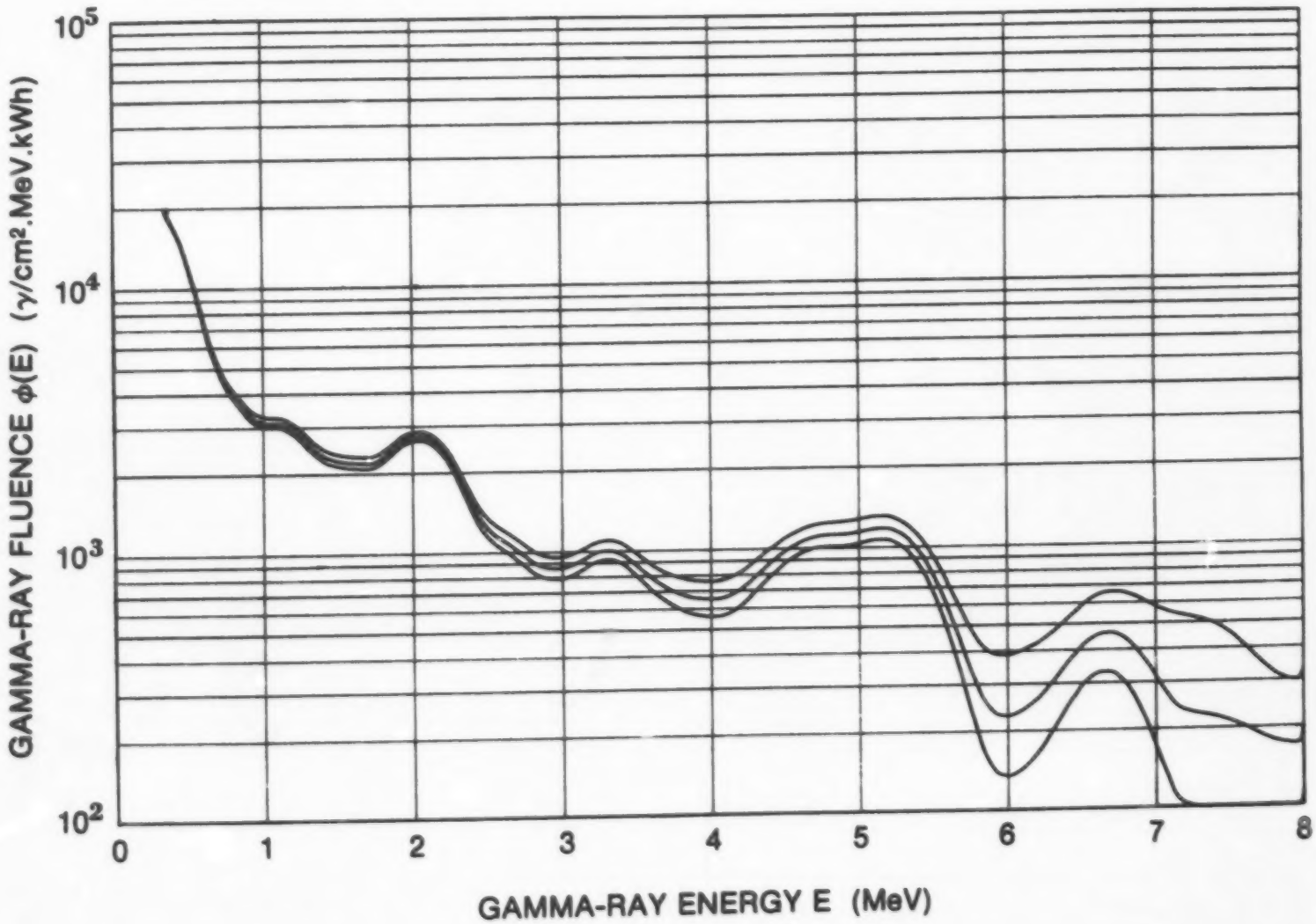

Figure B-8: Free-Field Gamme-Ray Spectrum Obtained at a Range of 1080 Meters (1980)

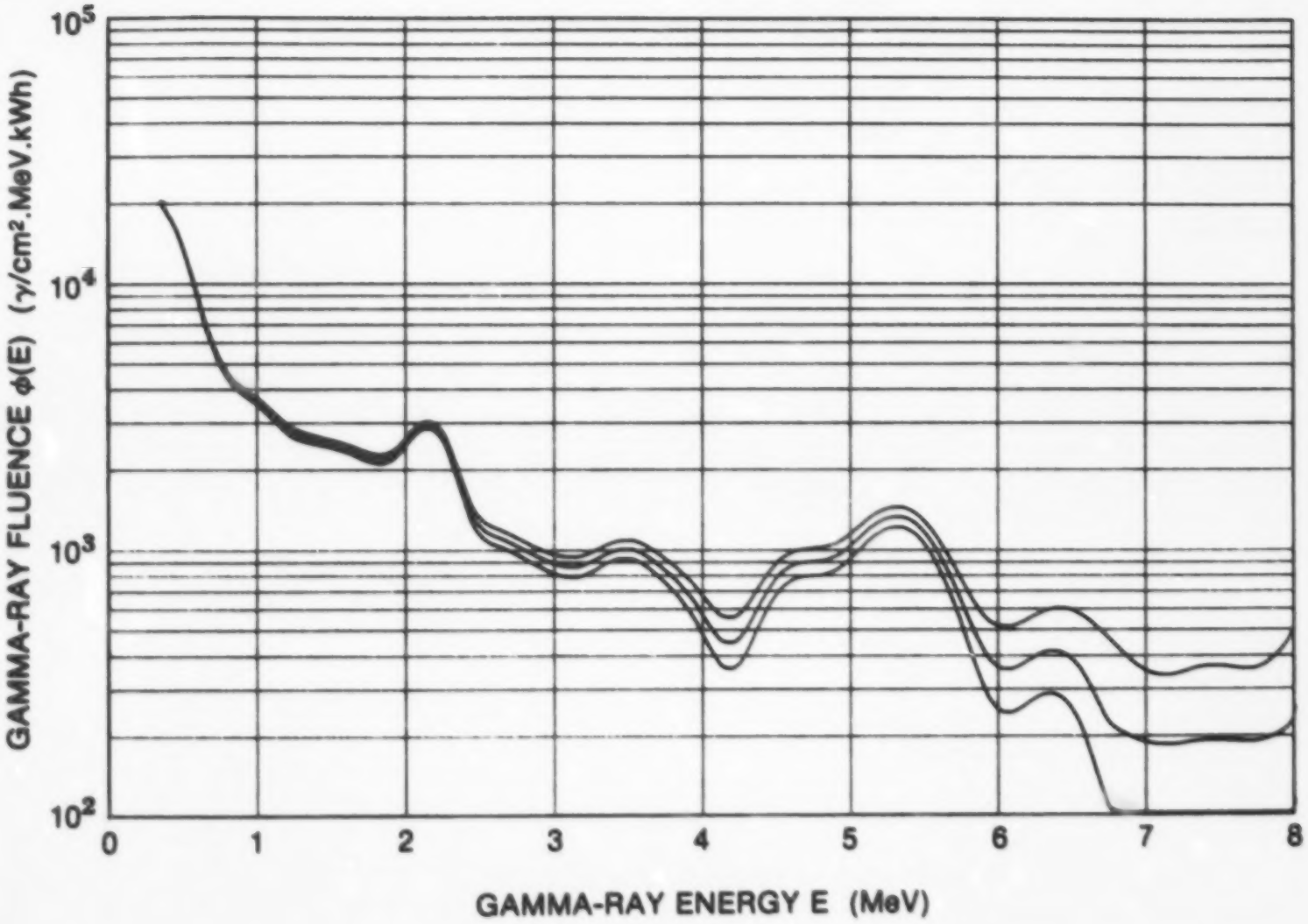

Figure B-9: Free-Field Gamma-Ray Spectrum Obtained at a Range of 1080 Meters (1981)

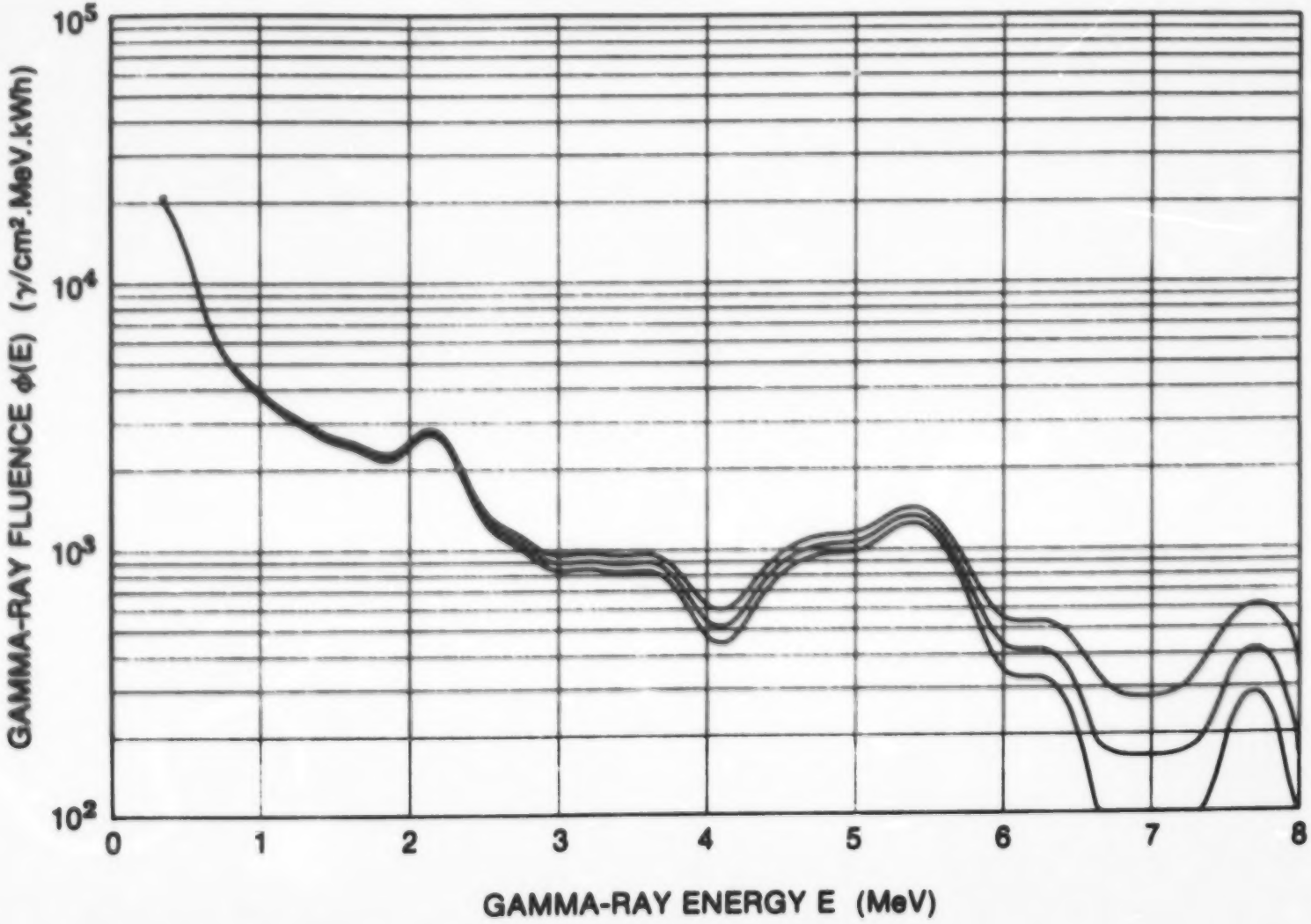

Figure B-10: Free-Field Gamma-Ray Spectrum Obtained at a Range of 1080 Meters, Under Conditions of High Temperature and Relative Humidity (1982)

APPENDIX C
LISTED FINE-GROUP NEUTRON SPECTRA

APPENDIX C: LISTED FINE-GROUP NEUTRON SPECTRA

The following listed data comprise neutron spectra as analysed by DREO unfolding techniques corresponding to the plotted data of Appendix A. Data obtained by the NE-213 detector are shown in a multigroup format starting at 600 KeV and continuing to 10 MeV in 200 KeV increments. These data are normalized such that the applicable units are "neutrons per cm^2.MeV.KWh" within each energy group. Two additional quantities are also listed for each spectrum, labelled "Thermal Flux" and "Epithermals". These correspond to estimates of the total neutron fluence between 0 and 0.5 eV and between 0.5 eV and 600 KeV, respectively. As such the units are different and correspond to "neutrons per cm^2.KWh" between the previously-specified energy limits. This difference in normalization is taken into consideration in the calculation of integral fluence listed in the last column.

The thermal neutron fluence was measured using a pair of matched boron-triflouride counters, one of which was lined on the outside with 0.102 cm of cadmium. The cadmium-lined counter is insensitive to neutrons below 0.5 eV (50% transmission probability) and consequently monitors neutrons only above this energy. The difference in recorded counts between the two detectors is thus a measure of neutron fluence below 0.5 eV. The thermal neutron component was assumed to be Maxwellian in spectral shape and in equilibrium at 20°C. Conversion to thermal neutron fluence was achieved by dividing by the mean thermal-neutron detection efficiency, as determined by integration of the energy-dependent counter efficiency (including the influence of the cadmium liner) over the above-mentioned Maxwellian.

The epithermal neutron fluence is estimated by assuming that the neutron spectrum between 0.5 eV and 600 KeV may be represented by a parametric equation of the form:

$$\phi(E) = A \cdot E^p$$

The magnitude A and power p are uniquely determined by simultaneously requiring that the parametric spectrum be continuous with the NE-213 determination at an energy of 600 KeV, and that the counting-rate recorded by the cadmium-lined BF_3 detector is reproduced when the energy-dependent detection efficiency is integrated against the parametric representation. Although this formulation ignores all structure present in the neutron spectrum below 600 KeV, integral quantities such as kerma or fluence are adequately determined in well-moderated neutron environments, such as exist at APRD.

For the ten neutron spectral determinations at APRD, the following parameters A and p were recorded:

RANGE	YEAR	A	p
15	1980	2.01 + 9	-0.769
100	1980	3.53 + 7	-0.886
170	1980	9.70 + 6	-0.913
179	1981	7.71 + 6	-0.923
260	1981	1.93 + 6	-0.943
300	1980	1.31 + 6	-0.942
400	1980	4.31 + 5	-0.956
1080	1980	1.59 + 3	-0.975
1080	1981	1.50 + 3	-0.977
1080	1982	1.58 + 3	-0.956

The parameter A is scaled such that the parametric spectrum $\phi(E) = A E^p$ reproduces the neutron spectrum in units of "neutrons per cm^2.MeV.KWh". It is worthy of note that as ground range increases the parameter p tends to the classic expectation of -1 (1/E variation), indicating the increasing degree of moderation. Since the last point at 1080 meters was obtained under conditions of high temperature and humidty, the slight reduction in p observed in 1982 indicates a certain spectral hardening, probably due to increased absorption by the additional intervening hydrogen.

Note that the indicated errors refer only to the uncertainty introduced by the unfolding procedure and neglect the contribution due to reactor power reproducibility (2%).

C-1: Neutron spectrum at a range of 15m (1980).

GROUP	UPPER ENERGY (MEV)	PARTICLE FLUX (PARTICLES/ CM2-MEV-KWH)	ERROR (STD. DEV.)	ERROR (%)	RUNNING INTEGRAL (/CM2-KWH)
THERMAL FLUX		5.704E+08	1.23E+06	0.22	5.704E+08
EPITHERMALS		7.440E+09	4.31E+07	0.58	8.010E+09
4	0.8	2.736E+09	1.28E+07	0.47	8.557E+09
5	1.0	2.048E+09	1.00E+07	0.49	8.967E+09
6	1.2	1.681E+09	1.04E+07	0.62	9.303E+09
7	1.4	1.433E+09	1.09E+07	0.76	9.590E+09
8	1.6	1.273E+09	1.12E+07	0.88	9.845E+09
9	1.8	1.127E+09	1.14E+07	1.01	1.007E+10
10	2.0	9.912E+08	1.13E+07	1.14	1.027E+10
11	2.2	9.112E+08	1.11E+07	1.22	1.045E+10
12	2.4	8.169E+08	1.08E+07	1.32	1.061E+10
13	2.6	7.020E+08	1.02E+07	1.45	1.075E+10
14	2.8	6.112E+08	1.01E+07	1.65	1.088E+10
15	3.0	5.244E+08	9.97E+06	1.90	1.098E+10
16	3.2	4.603E+08	9.78E+06	2.12	1.107E+10
17	3.4	4.071E+08	9.55E+06	2.35	1.115E+10
18	3.6	3.573E+08	9.33E+06	2.61	1.123E+10
19	3.8	3.107E+08	9.12E+06	2.94	1.129E+10
20	4.0	2.826E+08	8.91E+06	3.15	1.135E+10
21	4.2	2.583E+08	8.62E+06	3.32	1.140E+10
22	4.4	2.324E+08	8.27E+06	3.56	1.144E+10
23	4.6	2.106E+08	7.88E+06	3.74	1.148E+10
24	4.8	1.888E+08	7.48E+06	3.95	1.152E+10
25	5.0	1.565E+08	7.06E+06	4.51	1.155E+10
26	5.2	1.342E+08	6.72E+06	5.01	1.158E+10
27	5.4	1.261E+08	6.34E+06	5.03	1.161E+10
28	5.6	1.088E+08	5.81E+06	5.38	1.163E+10
29	5.8	8.573E+07	5.55E+06	6.47	1.165E+10
30	6.0	7.022E+07	5.37E+06	7.65	1.166E+10
31	6.2	6.456E+07	5.21E+06	8.08	1.167E+10
32	6.4	6.029E+07	5.01E+06	8.30	1.168E+10
33	6.6	5.267E+07	4.74E+06	9.01	1.170E+10
34	6.8	4.410E+07	4.47E+06	10.14	1.170E+10
35	7.0	3.757E+07	4.30E+06	11.46	1.171E+10
36	7.2	3.102E+07	4.19E+06	13.50	1.172E+10
37	7.4	2.637E+07	4.08E+06	15.47	1.172E+10
38	7.6	2.688E+07	3.90E+06	14.52	1.173E+10
39	7.8	2.793E+07	3.72E+06	13.33	1.173E+10
40	8.0	2.587E+07	3.50E+06	13.46	1.174E+10
41	8.2	2.282E+07	3.23E+06	14.16	1.174E+10
42	8.4	1.882E+07	2.93E+06	15.68	1.175E+10
43	8.6	1.348E+07	2.71E+06	20.10	1.175E+10
44	8.8	9.414E+06	2.55E+06	27.04	1.175E+10
45	9.0	8.216E+06	2.43E+06	29.58	1.175E+10
46	9.2	8.160E+06	2.29E+06	28.09	1.176E+10
47	9.4	8.130E+06	2.16E+06	26.56	1.176E+10
48	9.6	8.603E+06	2.04E+06	23.69	1.176E+10
49	9.8	8.541E+06	1.86E+06	21.79	1.176E+10
50	10.0	7.077E+06	1.67E+06	23.66	1.176E+10

C-2: Neutron spectrum at a range of 100m (1980).

GROUP	UPPER ENERGY (MEV)	PARTICLE FLUX (PARTICLES/ CM2-MEV-KWH)	ERROR (STD. DEV.)	ERROR (%)	RUNNING INTEGRAL (/CM2-KWH)
THERMAL FLUX		5.258E+07	6.40E+04	0.12	5.258E+07
EPITHERMALS		2.335E+08	9.11E+05	0.39	2.861E+08
4	0.8	5.087E+07	2.84E+05	0.56	2.963E+08
5	1.0	3.526E+07	2.18E+05	0.62	3.033E+08
6	1.2	2.788E+07	2.23E+05	0.81	3.089E+08
7	1.4	2.352E+07	2.34E+05	1.00	3.136E+08
8	1.6	2.001E+07	2.40E+05	1.20	3.176E+08
9	1.8	1.803E+07	2.44E+05	1.35	3.212E+08
10	2.0	1.670E+07	2.41E+05	1.44	3.246E+08
11	2.2	1.547E+07	2.34E+05	1.52	3.277E+08
12	2.4	1.376E+07	2.24E+05	1.63	3.304E+08
13	2.6	1.163E+07	2.09E+05	1.80	3.327E+08
14	2.8	9.668E+06	2.08E+05	2.13	3.347E+08
15	3.0	8.106E+06	2.01E+05	2.48	3.363E+08
16	3.2	6.903E+06	1.85E+05	2.83	3.377E+08
17	3.4	5.604E+06	1.90E+05	3.39	3.388E+08
18	3.6	4.670E+06	1.86E+05	3.98	3.397E+08
19	3.8	4.160E+06	1.83E+05	4.41	3.406E+08
20	4.0	3.935E+06	1.80E+05	4.58	3.413E+08
21	4.2	3.661E+06	1.75E+05	4.79	3.421E+08
22	4.4	3.228E+06	1.70E+05	5.25	3.427E+08
23	4.6	2.888E+06	1.63E+05	5.65	3.433E+08
24	4.8	2.584E+06	1.56E+05	6.04	3.438E+08
25	5.0	2.429E+06	1.48E+05	6.10	3.443E+08
26	5.2	2.206E+06	1.38E+05	6.23	3.447E+08
27	5.4	1.865E+06	1.31E+05	7.01	3.451E+08
28	5.6	1.679E+06	1.22E+05	7.27	3.454E+08
29	5.8	1.461E+06	1.13E+05	7.74	3.457E+08
30	6.0	1.130E+06	1.07E+05	9.50	3.460E+08
31	6.2	8.799E+05	1.04E+05	11.78	3.461E+08
32	6.4	7.172E+05	9.85E+04	13.83	3.463E+08
33	6.6	6.066E+05	9.60E+04	15.83	3.464E+08
34	6.8	6.102E+05	9.13E+04	14.96	3.465E+08
35	7.0	6.001E+05	8.68E+04	14.48	3.466E+08
36	7.2	5.028E+05	8.35E+04	16.60	3.467E+08
37	7.4	4.145E+05	8.02E+04	19.35	3.468E+08
38	7.6	3.463E+05	7.60E+04	21.94	3.469E+08
39	7.8	3.073E+05	7.33E+04	23.86	3.470E+08
40	8.0	2.885E+05	6.96E+04	24.04	3.470E+08
41	8.2	2.608E+05	6.91E+04	26.95	3.471E+08
42	8.4	2.487E+05	6.08E+04	24.37	3.471E+08
43	8.6	2.296E+05	5.92E+04	24.02	3.472E+08
44	8.8	1.799E+05	5.03E+04	27.94	3.472E+08
45	9.0	1.424E+05	4.70E+04	32.99	3.472E+08
46	9.2	1.359E+05	4.38E+04	32.23	3.473E+08
47	9.4	1.290E+05	3.97E+04	30.75	3.473E+08
48	9.6	9.625E+04	3.62E+04	37.63	3.473E+08
49	9.8	6.718E+04	3.51E+04	52.26	3.473E+08
50	10.0	6.098E+04	3.37E+04	55.19	3.473E+08

C-3: Neutron spectrum at a range of 170m (1980).

GROUP	UPPER ENERGY (MEV)	PARTICLE FLUX (PARTICLES/ CM2-MEV-MAH)	ERROR (STD. DEV.)	ERROR (%)	RUNNING INTEGRAL (/CM2-MAH)
THERMAL FLUX		1.898E+07	1.94E+04	0.10	1.898E+07
EPITHERMALS		7.500E+07	2.38E+05	0.32	9.398E+07
4	0.8	1.419E+07	7.39E+04	0.52	9.883E+07
5	1.0	8.601E+06	5.67E+04	0.59	9.873E+07
6	1.2	7.678E+06	5.82E+04	0.76	1.003E+08
7	1.4	6.211E+06	6.08E+04	0.98	1.015E+08
8	1.6	5.338E+06	6.21E+04	1.16	1.026E+08
9	1.8	4.820E+06	6.33E+04	1.31	1.036E+08
10	2.0	4.536E+06	6.25E+04	1.38	1.043E+08
11	2.2	4.263E+06	6.05E+04	1.42	1.053E+08
12	2.4	3.829E+06	5.75E+04	1.50	1.061E+08
13	2.6	3.198E+06	5.33E+04	1.67	1.067E+08
14	2.8	2.682E+06	5.21E+04	1.94	1.073E+08
15	3.0	2.130E+06	5.06E+04	2.38	1.077E+08
16	3.2	1.688E+06	4.92E+04	2.92	1.080E+08
17	3.4	1.402E+06	4.80E+04	3.42	1.082E+08
18	3.6	1.153E+06	4.71E+04	3.85	1.083E+08
19	3.8	1.023E+06	4.65E+04	4.34	1.087E+08
20	4.0	9.294E+05	4.60E+04	4.95	1.089E+08
21	4.2	9.012E+05	4.52E+04	5.01	1.091E+08
22	4.4	8.803E+05	4.37E+04	4.96	1.093E+08
23	4.6	7.624E+05	4.18E+04	5.48	1.094E+08
24	4.8	6.285E+05	4.03E+04	6.41	1.096E+08
25	5.0	5.203E+05	3.86E+04	6.22	1.097E+08
26	5.2	6.120E+05	3.63E+04	5.93	1.098E+08
27	5.4	5.283E+05	3.38E+04	6.42	1.099E+08
28	5.6	4.388E+05	3.16E+04	7.18	1.100E+08
29	5.8	3.505E+05	2.95E+04	8.41	1.101E+08
30	6.0	2.783E+05	2.83E+04	10.18	1.101E+08
31	6.2	2.348E+05	2.75E+04	11.72	1.102E+08
32	6.4	2.121E+05	2.68E+04	12.53	1.102E+08
33	6.6	2.034E+05	2.52E+04	12.41	1.103E+08
34	6.8	1.848E+05	2.35E+04	12.75	1.103E+08
35	7.0	1.523E+05	2.24E+04	14.71	1.103E+08
36	7.2	1.293E+05	2.17E+04	16.84	1.104E+08
37	7.4	1.284E+05	2.07E+04	16.11	1.104E+08
38	7.6	1.131E+05	1.93E+04	17.07	1.104E+08
39	7.8	8.843E+04	1.82E+04	20.59	1.104E+08
40	8.0	6.032E+04	1.74E+04	28.83	1.104E+08
41	8.2	4.638E+04	1.68E+04	36.09	1.104E+08
42	8.4	4.863E+04	1.60E+04	32.22	1.105E+08
43	8.6	5.341E+04	1.48E+04	27.78	1.105E+08
44	8.8	5.088E+04	1.36E+04	26.81	1.105E+08
45	9.0	4.348E+04	1.27E+04	29.19	1.105E+08
46	9.2	3.778E+04	1.19E+04	31.51	1.105E+08
47	9.4	3.622E+04	1.09E+04	30.21	1.105E+08
48	9.6	3.236E+04	9.78E+03	30.24	1.105E+08
49	9.8	2.650E+04	8.84E+03	33.09	1.105E+08
50	10.0	1.835E+04	8.24E+03	43.49	1.105E+08

C-4: Neutron spectrum at a range of 179m (1981).

GROUP	UPPER ENERGY (MEV)	PARTICLE FLUX (PARTICLES/ CM2-MEV-MAH)	ERROR (STD. DEV.)	ERROR (%)	RUNNING INTEGRAL (/CM2-MAH)
THERMAL FLUX		2.034E+07	1.48E+04	0.07	2.034E+07
EPITHERMALS		8.353E+07	1.58E+05	0.25	8.386E+07
4	0.8	1.118E+07	4.88E+04	0.44	8.610E+07
5	1.0	7.778E+06	3.75E+04	0.48	8.765E+07
6	1.2	6.253E+06	3.85E+04	0.62	8.890E+07
7	1.4	5.054E+06	4.01E+04	0.79	8.991E+07
8	1.6	4.367E+06	4.12E+04	0.94	9.078E+07
9	1.8	4.094E+06	4.18E+04	1.02	9.161E+07
10	2.0	3.877E+06	4.11E+04	1.06	9.238E+07
11	2.2	3.648E+06	3.94E+04	1.08	9.311E+07
12	2.4	3.220E+06	3.71E+04	1.15	9.376E+07
13	2.6	2.653E+06	3.40E+04	1.28	9.429E+07
14	2.8	2.103E+06	3.30E+04	1.57	9.471E+07
15	3.0	1.628E+06	3.20E+04	1.96	9.503E+07
16	3.2	1.304E+06	3.11E+04	2.38	9.529E+07
17	3.4	1.048E+06	3.02E+04	2.89	9.550E+07
18	3.6	8.426E+05	2.98E+04	3.53	9.567E+07
19	3.8	7.302E+05	2.95E+04	4.05	9.582E+07
20	4.0	7.011E+05	2.83E+04	4.18	9.596E+07
21	4.2	6.620E+05	2.88E+04	4.34	9.609E+07
22	4.4	5.834E+05	2.80E+04	4.80	9.621E+07
23	4.6	5.733E+05	2.72E+04	4.74	9.632E+07
24	4.8	5.833E+05	2.59E+04	4.44	9.644E+07
25	5.0	5.356E+05	2.44E+04	4.56	9.655E+07
26	5.2	4.806E+05	2.29E+04	4.96	9.664E+07
27	5.4	3.832E+05	2.14E+04	5.58	9.671E+07
28	5.6	3.122E+05	2.00E+04	6.41	9.678E+07
29	5.8	2.495E+05	1.88E+04	7.54	9.683E+07
30	6.0	2.052E+05	1.82E+04	8.85	9.687E+07
31	6.2	1.805E+05	1.76E+04	9.78	9.690E+07
32	6.4	1.695E+05	1.70E+04	10.05	9.694E+07
33	6.6	1.591E+05	1.61E+04	10.14	9.697E+07
34	6.8	1.380E+05	1.51E+04	10.88	9.700E+07
35	7.0	1.195E+05	1.45E+04	12.10	9.702E+07
36	7.2	1.038E+05	1.39E+04	13.38	9.704E+07
37	7.4	8.564E+04	1.33E+04	15.56	9.706E+07
38	7.6	7.156E+04	1.27E+04	17.70	9.707E+07
39	7.8	6.730E+04	1.22E+04	18.06	9.709E+07
40	8.0	6.287E+04	1.15E+04	18.26	9.710E+07
41	8.2	5.392E+04	1.08E+04	19.95	9.711E+07
42	8.4	4.629E+04	1.01E+04	21.71	9.712E+07
43	8.6	3.878E+04	9.33E+03	23.45	9.713E+07
44	8.8	3.401E+04	8.68E+03	25.51	9.713E+07
45	9.0	3.135E+04	8.13E+03	25.94	9.714E+07
46	9.2	2.502E+04	7.36E+03	26.05	9.715E+07
47	9.4	2.433E+04	7.01E+03	28.79	9.715E+07
48	9.6	1.938E+04	6.54E+03	33.37	9.715E+07
49	9.8	1.708E+04	6.11E+03	35.78	9.716E+07
50	10.0	1.624E+04	5.65E+03	34.79	9.718E+07

C-5: Neutron spectrum at a range of 260m (1981).

GROUP	UPPER ENERGY (MEV)	PARTICLE FLUX (PARTICLES/ CM2-MEV-SUM)	ERROR (STD. DEV.)	ERROR (%)	RUNNING INTEGRAL (/CM2-SUM)
THERMAL FLUX		6.712E+06	5.11E+03	0.08	6.712E+06
EPITHERMALS		1.807E+07	4.83E+04	0.27	2.479E+07
4	0.8	2.860E+06	1.50E+04	0.52	2.936E+07
5	1.0	1.897E+06	1.38E+04	0.73	2.574E+07
6	1.2	1.553E+06	1.48E+04	0.95	2.605E+07
7	1.4	1.267E+06	1.59E+04	1.25	2.630E+07
8	1.6	1.034E+06	1.68E+04	1.62	2.651E+07
9	1.8	1.039E+06	1.75E+04	1.69	2.672E+07
10	2.0	1.075E+06	1.74E+04	1.62	2.693E+07
11	2.2	9.976E+05	1.69E+04	1.69	2.713E+07
12	2.4	8.651E+05	1.60E+04	1.85	2.730E+07
13	2.6	7.086E+05	1.47E+04	2.08	2.745E+07
14	2.8	5.236E+05	1.44E+04	2.75	2.755E+07
15	3.0	4.047E+05	1.41E+04	3.49	2.763E+07
16	3.2	3.005E+05	1.38E+04	4.61	2.769E+07
17	3.4	2.284E+05	1.37E+04	6.02	2.774E+07
18	3.6	1.956E+05	1.38E+04	6.89	2.778E+07
19	3.8	1.641E+05	1.38E+04	8.43	2.781E+07
20	4.0	1.795E+05	1.35E+04	7.75	2.785E+07
21	4.2	1.701E+05	1.38E+04	8.09	2.788E+07
22	4.4	1.417E+05	1.35E+04	9.55	2.791E+07
23	4.6	1.310E+05	1.33E+04	10.13	2.793E+07
24	4.8	1.270E+05	1.29E+04	10.19	2.796E+07
25	5.0	1.511E+05	1.24E+04	8.18	2.799E+07
26	5.2	1.376E+05	1.15E+04	8.38	2.802E+07
27	5.4	1.108E+05	1.08E+04	9.72	2.804E+07
28	5.6	8.742E+04	1.00E+04	11.48	2.806E+07
29	5.8	6.743E+04	9.37E+03	13.90	2.807E+07
30	6.0	5.052E+04	9.13E+03	17.94	2.808E+07
31	6.2	4.731E+04	8.97E+03	18.95	2.809E+07
32	6.4	4.663E+04	8.64E+03	18.53	2.810E+07
33	6.6	4.218E+04	8.20E+03	19.44	2.811E+07
34	6.8	3.492E+04	7.64E+03	21.89	2.812E+07
35	7.0	2.378E+04	7.46E+03	31.37	2.812E+07
36	7.2	3.020E+04	7.31E+03	24.20	2.813E+07
37	7.4	3.310E+04	6.84E+03	20.66	2.813E+07
38	7.6	1.707E+04	6.49E+03	38.00	2.814E+07
39	7.8	1.048E+04	6.52E+03	62.23	2.814E+07
40	8.0	1.527E+04	6.37E+03	41.68	2.814E+07
41	8.2	1.790E+04	6.00E+03	33.52	2.814E+07
42	8.4	1.344E+04	5.56E+03	41.36	2.815E+07
43	8.6	7.405E+03	5.25E+03	70.86	2.815E+07
44	8.8	8.020E+03	5.02E+03	62.58	2.815E+07
45	9.0	9.862E+03	4.74E+03	48.08	2.815E+07
46	9.2	8.844E+03	4.42E+03	50.03	2.815E+07
47	9.4	7.958E+03	4.12E+03	51.74	2.816E+07
48	9.6	7.425E+03	3.78E+03	50.59	2.816E+07
49	9.8	4.850E+03	3.38E+03	69.79	2.816E+07
50	10.0	1.896E+03	3.14E+03	165.71	2.816E+07

C-6: Neutron spectrum at a range of 300m (1980).

GROUP	UPPER ENERGY (MEV)	PARTICLE FLUX (PARTICLES/ CM2-MEV-SUM)	ERROR (STD. DEV.)	ERROR (%)	RUNNING INTEGRAL (/CM2-SUM)
THERMAL FLUX		4.504E+06	4.13E+03	0.09	4.504E+06
EPITHERMALS		1.221E+07	3.92E+04	0.32	1.671E+07
4	0.8	1.946E+06	1.22E+04	0.63	1.710E+07
5	1.0	1.284E+06	9.34E+03	0.73	1.736E+07
6	1.2	1.013E+06	9.65E+03	0.95	1.756E+07
7	1.4	8.108E+05	1.01E+04	1.25	1.772E+07
8	1.6	7.023E+05	1.05E+04	1.50	1.786E+07
9	1.8	6.686E+05	1.08E+04	1.61	1.799E+07
10	2.0	6.606E+05	1.06E+04	1.61	1.813E+07
11	2.2	6.403E+05	1.03E+04	1.60	1.825E+07
12	2.4	5.679E+05	9.68E+03	1.71	1.837E+07
13	2.6	4.815E+05	8.90E+03	1.85	1.846E+07
14	2.8	3.870E+05	8.61E+03	2.22	1.854E+07
15	3.0	3.036E+05	8.33E+03	2.74	1.860E+07
16	3.2	2.373E+05	8.08E+03	3.41	1.865E+07
17	3.4	1.879E+05	7.83E+03	4.20	1.869E+07
18	3.6	1.483E+05	7.79E+03	5.25	1.872E+07
19	3.8	1.228E+05	7.77E+03	6.33	1.874E+07
20	4.0	1.129E+05	7.79E+03	6.90	1.876E+07
21	4.2	1.084E+05	7.74E+03	7.14	1.879E+07
22	4.4	1.027E+05	7.61E+03	7.41	1.881E+07
23	4.6	9.765E+04	7.43E+03	7.61	1.883E+07
24	4.8	1.025E+05	7.19E+03	7.02	1.885E+07
25	5.0	1.090E+05	6.82E+03	6.25	1.887E+07
26	5.2	9.993E+04	6.36E+03	6.37	1.889E+07
27	5.4	8.440E+04	5.91E+03	7.01	1.891E+07
28	5.6	6.595E+04	5.40E+03	8.31	1.892E+07
29	5.8	4.844E+04	5.18E+03	10.69	1.893E+07
30	6.0	4.261E+04	5.02E+03	11.77	1.894E+07
31	6.2	3.932E+04	4.82E+03	12.26	1.894E+07
32	6.4	3.262E+04	4.63E+03	14.20	1.895E+07
33	6.6	3.000E+04	4.44E+03	14.79	1.896E+07
34	6.8	3.026E+04	4.14E+03	13.69	1.896E+07
35	7.0	2.554E+04	3.90E+03	15.26	1.897E+07
36	7.2	1.824E+04	3.78E+03	20.63	1.897E+07
37	7.4	1.401E+04	3.66E+03	26.14	1.897E+07
38	7.6	1.340E+04	3.53E+03	26.34	1.898E+07
39	7.8	1.424E+04	3.35E+03	23.78	1.898E+07
40	8.0	1.418E+04	3.18E+03	22.40	1.898E+07
41	8.2	1.247E+04	2.94E+03	23.52	1.899E+07
42	8.4	9.178E+03	2.70E+03	29.47	1.899E+07
43	8.6	6.171E+03	2.52E+03	40.88	1.899E+07
44	8.8	5.750E+03	2.38E+03	41.52	1.899E+07
45	9.0	6.360E+03	2.24E+03	35.26	1.899E+07
46	9.2	5.622E+03	2.09E+03	37.18	1.899E+07
47	9.4	4.403E+03	1.99E+03	45.09	1.899E+07
48	9.6	4.058E+03	1.90E+03	46.73	1.899E+07
49	9.8	4.646E+03	1.78E+03	38.22	1.899E+07
50	10.0	5.045E+03	1.59E+03	31.52	1.900E+07

C-7: Neutron spectrum at a range of 400m (1980).

GROUP	UPPER ENERGY (MEV)	PARTICLE FLUX (PARTICLES/ CM2-MEV-KWH)	ERROR (STD. DEV.)	ERROR (%)	RUNNING INTEGRAL (/CM2-KWH)
THERMAL FLUX		1.580E+06	1.12E+03	0.07	1.580E+06
EPITHERMALS		4.403E+06	1.03E+04	0.23	5.982E+06
4	0.8	6.499E+05	3.10E+03	0.48	6.112E+06
5	1.0	4.173E+05	2.38E+03	0.57	6.196E+06
6	1.2	3.310E+05	2.45E+03	0.74	6.262E+06
7	1.4	2.651E+05	2.57E+03	0.97	6.315E+06
8	1.6	2.247E+05	2.66E+03	1.19	6.360E+06
9	1.8	2.095E+05	2.74E+03	1.31	6.402E+06
10	2.0	2.111E+05	2.71E+03	1.28	6.444E+06
11	2.2	2.075E+05	2.61E+03	1.26	5.486E+06
12	2.4	1.898E+05	2.46E+03	1.30	6.524E+06
13	2.6	1.640E+05	2.25E+03	1.37	6.556E+06
14	2.8	1.288E+05	2.15E+03	1.67	6.582E+06
15	3.0	9.719E+04	2.07E+03	2.13	6.602E+06
16	3.2	7.407E+04	2.01E+03	2.71	6.616E+06
17	3.4	5.991E+04	1.96E+03	3.51	6.628E+06
18	3.6	4.340E+04	1.95E+03	4.50	6.636E+06
19	3.8	3.582E+04	1.96E+03	5.47	6.643E+06
20	4.0	3.244E+04	1.98E+03	6.10	6.650E+06
21	4.2	3.199E+04	1.98E+03	6.20	6.656E+06
22	4.4	3.105E+04	1.96E+03	6.32	6.663E+06
23	4.6	2.927E+04	1.93E+03	6.59	6.668E+06
24	4.8	2.877E+04	1.88E+03	6.53	6.674E+06
25	5.0	3.227E+04	1.81E+03	5.62	6.681E+06
26	5.2	3.281E+04	1.72E+03	5.23	6.687E+06
27	5.4	3.043E+04	1.60E+03	5.27	6.693E+06
28	5.6	2.523E+04	1.48E+03	5.87	6.698E+06
29	5.8	1.941E+04	1.39E+03	7.15	6.702E+06
30	6.0	1.559E+04	1.34E+03	8.57	6.705E+06
31	6.2	1.314E+04	1.29E+03	9.85	6.708E+06
32	6.4	1.073E+04	1.25E+03	11.65	6.710E+06
33	6.6	8.861E+03	1.20E+03	13.44	6.712E+06
34	6.8	8.967E+03	1.13E+03	12.84	6.714E+06
35	7.0	9.620E+03	1.10E+03	11.48	6.716E+06
36	7.2	9.279E+03	1.05E+03	11.34	6.718E+06
37	7.4	7.919E+03	9.92E+02	12.53	6.719E+06
38	7.6	5.940E+03	8.25E+02	15.58	6.720E+06
39	7.8	4.448E+03	8.88E+02	19.96	6.721E+06
40	8.0	4.036E+03	8.52E+02	21.12	6.722E+06
41	8.2	3.760E+03	8.03E+02	21.37	6.723E+06
42	8.4	3.205E+03	7.52E+02	23.47	6.723E+06
43	8.6	2.727E+03	7.03E+02	25.78	6.724E+06
44	8.8	2.428E+03	6.55E+02	26.98	6.725E+06
45	9.0	2.102E+03	6.16E+02	29.28	6.725E+06
46	9.2	1.803E+03	5.85E+02	32.47	6.725E+06
47	9.4	1.726E+03	5.56E+02	32.21	6.726E+06
48	9.6	1.642E+03	5.17E+02	31.48	6.726E+06
49	9.8	1.381E+03	4.80E+02	34.74	6.726E+06
50	10.0	1.246E+03	4.51E+02	36.16	6.727E+06

C-8: Neutron spectrum at a range of 1080m (1980).

GROUP	UPPER ENERGY (MEV)	PARTICLE FLUX (PARTICLES/ CM2-MEV-KWH)	ERROR (STD. DEV.)	ERROR (%)	RUNNING INTEGRAL (/CM2-KWH)
THERMAL FLUX		4.790E+03	9.82E+00	0.20	4.790E+03
EPITHERMALS		1.653E+04	9.77E+01	0.53	2.332E+04
4	0.8	2.390E+03	2.98E+01	1.25	2.380E+04
5	1.0	1.551E+03	2.28E+01	1.47	2.411E+04
6	1.2	1.231E+03	2.34E+01	1.90	2.436E+04
7	1.4	9.598E+02	2.45E+01	2.55	2.455E+04
8	1.6	8.089E+02	2.54E+01	3.14	2.471E+04
9	1.8	7.818E+02	2.60E+01	3.33	2.487E+04
10	2.0	8.044E+02	2.56E+01	3.18	2.503E+04
11	2.2	7.780E+02	2.43E+01	3.12	2.518E+04
12	2.4	7.356E+02	2.24E+01	3.05	2.533E+04
13	2.6	5.900E+02	2.01E+01	3.41	2.545E+04
14	2.8	4.213E+02	1.92E+01	4.55	2.553E+04
15	3.0	2.630E+02	1.87E+01	7.09	2.558E+04
16	3.2	1.828E+02	1.84E+01	10.09	2.562E+04
17	3.4	1.411E+02	1.83E+01	12.96	2.565E+04
18	3.6	1.234E+02	1.86E+01	15.06	2.567E+04
19	3.8	1.126E+02	1.91E+01	16.96	2.570E+04
20	4.0	8.376E+01	1.96E+01	23.45	2.571E+04
21	4.2	8.427E+01	2.00E+01	23.72	2.573E+04
22	4.4	1.156E+02	1.99E+01	17.22	2.575E+04
23	4.6	1.350E+02	1.96E+01	14.49	2.578E+04
24	4.8	1.414E+02	1.89E+01	13.34	2.581E+04
25	5.0	1.482E+02	1.75E+01	11.79	2.584E+04
26	5.2	1.335E+02	1.61E+01	12.05	2.586E+04
27	5.4	1.032E+02	1.49E+01	14.47	2.589E+04
28	5.6	7.950E+01	1.40E+01	17.57	2.590E+04
29	5.8	6.684E+01	1.31E+01	19.62	2.591E+04
30	6.0	6.073E+01	1.26E+01	20.77	2.593E+04
31	6.2	5.952E+01	1.20E+01	20.23	2.594E+04
32	6.4	4.917E+01	1.12E+01	22.80	2.595E+04
33	6.6	3.096E+01	1.05E+01	33.78	2.595E+04
34	6.8	2.050E+01	1.01E+01	49.10	2.596E+04
35	7.0	2.233E+01	1.01E+01	45.12	2.596E+04
36	7.2	3.160E+01	9.95E+00	31.49	2.597E+04
37	7.4	3.738E+01	1.03E+01	27.27	2.598E+04
38	7.6	3.013E+01	1.20E+01	39.75	2.598E+04
39	7.8	1.561E+01	1.32E+01	84.72	2.598E+04
40	8.0	6.621E+00	1.16E+01	175.35	2.599E+04
41	8.2	5.798E+00	8.71E+00	150.33	2.599E+04
42	8.4	7.353E+00	6.92E+00	94.10	2.599E+04
43	8.6	6.262E+00	6.01E+00	96.04	2.599E+04
44	8.8	3.907E+00	5.74E+00	146.92	2.599E+04
45	9.0	3.782E+00	5.97E+00	157.97	2.599E+04
46	9.2	6.233E+00	6.01E+00	96.47	2.599E+04
47	9.4	8.725E+00	5.60E+00	64.21	2.600E+04
48	9.6	8.842E+00	4.82E+00	54.45	2.600E+04
49	9.8	7.134E+00	4.04E+00	56.60	2.600E+04
50	10.0	6.179E+00	3.74E+00	60.54	2.600E+04

C-9: Neutron spectrum at a range of 1080m (1981).

GROUP	UPPER ENERGY (MEV)	PARTICLE FLUX (PARTICLES/ CM2-MEV-KWH)	ERROR (STD. DEV.)	ERROR (%)	RUNNING INTEGRAL (/CM2-KWH)
THERMAL FLUX		5.068E+03	1.01E+01	0.20	5.068E+03
EPITHERMALS		1.773E+04	9.55E+01	0.54	2.280E+04
4	0.8	2.204E+03	2.96E+01	1.34	2.324E+04
5	1.0	1.524E+03	2.28E+01	1.50	2.354E+04
6	1.2	1.166E+03	2.34E+01	2.01	2.377E+04
7	1.4	9.211E+02	2.46E+01	2.67	2.396E+04
8	1.6	8.318E+02	2.53E+01	3.04	2.412E+04
9	1.8	9.004E+02	2.54E+01	2.83	2.430E+04
10	2.0	9.096E+02	2.43E+01	2.67	2.449E+04
11	2.2	8.018E+02	2.24E+01	2.80	2.465E+04
12	2.4	6.593E+02	2.04E+01	3.09	2.478E+04
13	2.6	4.726E+02	1.84E+01	3.88	2.487E+04
14	2.8	3.448E+02	1.77E+01	5.14	2.494E+04
15	3.0	2.270E+02	1.72E+01	7.59	2.499E+04
16	3.2	1.347E+02	1.72E+01	12.78	2.501E+04
17	3.4	1.017E+02	1.74E+01	17.14	2.504E+04
18	3.6	8.663E+01	1.78E+01	20.56	2.505E+04
19	3.8	7.360E+01	1.82E+01	24.69	2.507E+04
20	4.0	7.774E+01	1.85E+01	23.76	2.508E+04
21	4.2	1.077E+02	1.88E+01	17.46	2.510E+04
22	4.4	1.451E+02	1.91E+01	13.15	2.513E+04
23	4.6	1.419E+02	1.83E+01	12.92	2.516E+04
24	4.8	1.145E+02	1.73E+01	15.08	2.518E+04
25	5.0	1.152E+02	1.63E+01	14.18	2.521E+04
26	5.2	1.247E+02	1.46E+01	11.74	2.523E+04
27	5.4	1.054E+02	1.30E+01	12.29	2.525E+04
28	5.6	6.889E+01	1.18E+01	17.10	2.527E+04
29	5.8	5.119E+01	1.14E+01	22.22	2.528E+04
30	6.0	5.250E+01	1.19E+01	22.72	2.529E+04
31	6.2	4.428E+01	1.25E+01	28.18	2.530E+04
32	6.4	2.573E+01	1.19E+01	46.36	2.530E+04
33	6.6	1.477E+01	1.14E+01	76.97	2.530E+04
34	6.8	1.417E+01	1.06E+01	75.00	2.531E+04
35	7.0	2.057E+01	9.28E+00	45.12	2.531E+04
36	7.2	2.692E+01	9.13E+00	33.90	2.532E+04
37	7.4	2.365E+01	1.02E+01	43.08	2.532E+04
38	7.6	1.419E+01	9.62E+00	67.80	2.532E+04
39	7.8	8.087E+00	7.37E+00	91.00	2.533E+04
40	8.0	6.212E+00	6.79E+00	109.35	2.533E+04
41	8.2	5.333E+00	8.44E+00	158.16	2.533E+04
42	8.4	4.988E+00	9.53E+00	191.00	2.533E+04
43	8.6	6.473E+00	8.52E+00	131.63	2.533E+04
44	8.8	7.551E+00	6.25E+00	82.74	2.533E+04
45	9.0	5.444E+00	4.68E+00	95.90	2.533E+04
46	9.2	2.310E+00	4.24E+00	183.52	2.533E+04
47	9.4	5.557E-01	4.16E+00	747.70	2.533E+04
48	9.6	6.210E-02	3.91E+006304.77		2.533E+04
49	9.8	0.000E-01	3.46E+00	999.99	2.533E+04
50	10.0	0.000E-01	3.02E+00	999.99	2.533E+04

C-10: Neutron spectrum at a range of 1080m (1982).

GROUP	UPPER ENERGY (MEV)	PARTICLE FLUX (PARTICLES/ CM2-MEV-KWH)	ERROR (STD. DEV.)	ERROR (%)	RUNNING INTEGRAL (/CM2-KWH)
THERMAL FLUX		4.238E+03	7.50E+00	0.18	4.238E+03
EPITHERMALS		1.620E+04	7.88E+01	0.49	2.044E+04
4	0.8	2.324E+03	2.55E+01	1.10	2.090E+04
5	1.0	1.596E+03	1.98E+01	1.23	2.122E+04
6	1.2	1.272E+03	2.02E+01	1.59	2.148E+04
7	1.4	1.050E+03	2.12E+01	2.02	2.169E+04
8	1.6	8.699E+02	2.18E+01	2.50	2.186E+04
9	1.8	9.084E+02	2.21E+01	2.43	2.204E+04
10	2.0	9.645E+02	2.13E+01	2.21	2.224E+04
11	2.2	8.947E+02	2.00E+01	2.24	2.242E+04
12	2.4	7.776E+02	1.83E+01	2.36	2.257E+04
13	2.6	5.740E+02	1.63E+01	2.83	2.269E+04
14	2.8	4.085E+02	1.55E+01	3.79	2.277E+04
15	3.0	2.814E+02	1.51E+01	5.35	2.282E+04
16	3.2	2.058E+02	1.51E+01	7.31	2.286E+04
17	3.4	1.455E+02	1.50E+01	10.31	2.289E+04
18	3.6	8.774E+01	1.51E+01	17.22	2.291E+04
19	3.8	8.250E+01	1.57E+01	19.03	2.293E+04
20	4.0	1.099E+02	1.60E+01	14.59	2.295E+04
21	4.2	1.279E+02	1.59E+01	12.42	2.298E+04
22	4.4	1.254E+02	1.57E+01	12.49	2.300E+04
23	4.6	1.251E+02	1.55E+01	12.40	2.303E+04
24	4.8	1.391E+02	1.50E+01	10.75	2.305E+04
25	5.0	1.444E+02	1.39E+01	9.60	2.308E+04
26	5.2	1.298E+02	1.28E+01	9.85	2.311E+04
27	5.4	1.089E+02	1.18E+01	10.82	2.313E+04
28	5.6	8.909E+01	1.08E+01	12.14	2.315E+04
29	5.8	6.869E+01	1.01E+01	14.77	2.316E+04
30	6.0	5.342E+01	1.01E+01	18.87	2.317E+04
31	6.2	4.096E+01	9.76E+00	23.82	2.318E+04
32	6.4	3.505E+01	9.00E+00	25.68	2.319E+04
33	6.6	3.442E+01	8.35E+00	24.25	2.319E+04
34	6.8	3.359E+01	7.73E+00	23.02	2.320E+04
35	7.0	2.833E+01	7.23E+00	25.51	2.321E+04
36	7.2	2.003E+01	6.92E+00	34.56	2.321E+04
37	7.4	1.585E+01	6.70E+00	42.31	2.321E+04
38	7.6	1.531E+01	6.35E+00	41.48	2.322E+04
39	7.8	1.353E+01	6.04E+00	44.64	2.322E+04
40	8.0	1.117E+01	5.95E+00	53.26	2.322E+04
41	8.2	1.082E+01	6.57E+00	60.69	2.322E+04
42	8.4	1.110E+01	7.36E+00	66.33	2.323E+04
43	8.6	9.752E+00	6.82E+00	69.96	2.323E+04
44	8.8	8.275E+00	5.13E+00	62.24	2.323E+04
45	9.0	7.488E+00	3.91E+00	52.16	2.323E+04
46	9.2	6.272E+00	3.28E+00	52.34	2.323E+04
47	9.4	4.550E+00	2.87E+00	63.00	2.323E+04
48	9.6	3.602E+00	2.66E+00	73.83	2.323E+04
49	9.8	3.249E+00	2.50E+00	77.09	2.324E+04
50	10.0	2.431E+00	2.26E+00	93.12	2.324E+04

APPENDIX D
LISTED FINE-GROUP GAMMA-RAY SPECTRA

APPENDIX D: LISTED FINE-GROUP GAMMA-RAY SPECTRA

Gamma-ray data corresponding to the plotted spectra of Appendix B are listed on the following pages. The data have been obtained using an NE-213 organic scintillator and unfolded using DREO techniques. The spectra are listed in 100 KeV increments from 300 KeV to 8 MeV, and normalized to units of "photons per cm^2.MeV.kWh". As in Appendix B, there is no "Table D-1", since gamma-ray determinations at a range of 15 meters were prohibited due to excessive fission-product background.

D-2: Gamma-ray spectrum at a range of 100m (1980).

GROUP	UPPER ENERGY (MEV)	PARTICLE FLUX (PARTICLES/ CM2-MEV-KWH)	ERROR (STD. DEV.)	ERROR (%)	RUNNING INTEGRAL (/CM2-KWH)
4	0.4	1.098E+08	4.19E+05	0.38	1.098E+07
5	0.5	9.134E+07	2.90E+05	0.32	2.011E+07
6	0.6	5.598E+07	2.99E+05	0.53	2.571E+07
7	0.7	3.412E+07	3.19E+05	0.93	2.912E+07
8	0.8	2.717E+07	3.49E+05	1.29	3.184E+07
9	0.9	2.333E+07	3.70E+05	1.59	3.417E+07
10	1.0	2.039E+07	3.79E+05	1.86	3.621E+07
11	1.1	1.950E+07	3.72E+05	1.91	3.816E+07
12	1.2	1.941E+07	3.61E+05	1.86	4.010E+07
13	1.3	1.854E+07	3.53E+05	1.90	4.196E+07
14	1.4	1.654E+07	3.44E+05	2.08	4.361E+07
15	1.5	1.419E+07	3.36E+05	2.37	4.503E+07
16	1.6	1.257E+07	3.31E+05	2.64	4.629E+07
17	1.7	1.268E+07	3.31E+05	2.61	4.755E+07
18	1.8	1.527E+07	3.35E+05	2.20	4.908E+07
19	1.9	2.011E+07	3.37E+05	1.68	5.109E+07
20	2.0	2.416E+07	3.29E+05	1.36	5.351E+07
21	2.1	2.358E+07	3.09E+05	1.31	5.587E+07
22	2.2	1.837E+07	2.89E+05	1.58	5.770E+07
23	2.3	1.207E+07	2.77E+05	2.30	5.891E+07
24	2.4	7.022E+06	2.74E+05	3.90	5.969E+07
25	2.5	6.135E+06	2.74E+05	4.45	6.031E+07
26	2.6	5.688E+06	2.69E+05	4.73	6.088E+07
27	2.7	5.241E+06	2.61E+05	4.97	6.140E+07
28	2.8	4.787E+06	2.55E+05	5.32	6.188E+07
29	2.9	4.667E+06	2.51E+05	5.37	6.235E+07
30	3.0	4.821E+06	2.47E+05	5.13	6.283E+07
31	3.1	4.940E+06	2.44E+05	4.95	6.332E+07
32	3.2	4.839E+06	2.42E+05	5.00	6.381E+07
33	3.3	4.508E+06	2.41E+05	5.34	6.426E+07
34	3.4	4.067E+06	2.40E+05	5.91	6.466E+07
35	3.5	3.597E+06	2.41E+05	6.69	6.502E+07
36	3.6	3.149E+06	2.42E+05	7.70	6.534E+07
37	3.7	2.855E+06	2.46E+05	8.61	6.562E+07
38	3.8	2.650E+06	2.49E+05	9.40	6.589E+07
39	3.9	2.405E+06	2.53E+05	10.54	6.613E+07
40	4.0	2.198E+06	2.58E+05	11.76	6.635E+07
41	4.1	2.174E+06	2.63E+05	12.09	6.657E+07
42	4.2	2.320E+06	2.66E+05	11.45	6.680E+07
43	4.3	2.522E+06	2.68E+05	10.61	6.705E+07
44	4.4	2.710E+06	2.69E+05	9.91	6.732E+07
45	4.5	2.842E+06	2.69E+05	9.47	6.761E+07
46	4.6	2.882E+06	2.70E+05	9.35	6.789E+07
47	4.7	2.790E+06	2.70E+05	9.68	6.817E+07
48	4.8	2.567E+06	2.71E+05	10.57	6.843E+07
49	4.9	2.298E+06	2.73E+05	11.88	6.866E+07
50	5.0	2.091E+06	2.75E+05	13.16	6.887E+07
51	5.1	2.041E+06	2.76E+05	13.51	6.907E+07
52	5.2	2.125E+06	2.75E+05	12.94	6.928E+07
53	5.3	2.262E+06	2.74E+05	12.12	6.951E+07
54	5.4	2.345E+06	2.73E+05	11.63	6.975E+07
55	5.5	2.319E+06	2.71E+05	11.68	6.998E+07
56	5.6	2.160E+06	2.69E+05	12.44	7.019E+07
57	5.7	1.898E+06	2.68E+05	14.10	7.038E+07
58	5.8	1.594E+06	2.68E+05	16.82	7.054E+07
59	5.9	1.335E+06	2.71E+05	20.33	7.068E+07
60	6.0	1.189E+06	2.76E+05	23.22	7.079E+07
61	6.1	1.169E+06	2.80E+05	23.97	7.091E+07
62	6.2	1.247E+06	2.82E+05	22.63	7.104E+07
63	6.3	1.381E+06	2.82E+05	20.38	7.117E+07
64	6.4	1.549E+06	2.80E+05	18.07	7.133E+07
65	6.5	1.734E+06	2.76E+05	15.94	7.150E+07
66	6.6	1.916E+06	2.72E+05	14.19	7.169E+07
67	6.7	2.085E+06	2.67E+05	12.78	7.190E+07
68	6.8	2.217E+06	2.61E+05	11.77	7.212E+07
69	6.9	2.283E+06	2.55E+05	11.16	7.235E+07
70	7.0	2.269E+06	2.48E+05	10.92	7.258E+07
71	7.1	2.155E+06	2.40E+05	11.16	7.280E+07
72	7.2	1.959E+06	2.34E+05	11.93	7.299E+07
73	7.3	1.726E+06	2.29E+05	13.25	7.316E+07
74	7.4	1.492E+06	2.26E+05	15.15	7.331E+07
75	7.5	1.296E+06	2.27E+05	17.50	7.344E+07
76	7.6	1.154E+06	2.30E+05	19.97	7.356E+07
77	7.7	1.063E+06	2.35E+05	22.08	7.366E+07
78	7.8	1.018E+06	2.37E+05	23.31	7.377E+07
79	7.9	8.956E+05	2.38E+05	23.87	7.387E+07
80	8.0	8.753E+05	2.38E+05	24.36	7.396E+07

D-3: Gamma-ray spectrum at a range of 170m (1980).

GROUP	UPPER ENERGY (MEV)	PARTICLE FLUX (PARTICLES/ CM2-MEV-KWH)	ERROR (STD. DEV.)	ERROR (%)	RUNNING INTEGRAL (/CM2-KWH)
4	0.4	3.826E+07	1.09E+05	0.28	3.826E+06
5	0.5	3.150E+07	7.44E+04	0.24	6.976E+06
6	0.6	1.894E+07	7.49E+04	0.40	8.870E+06
7	0.7	1.111E+07	7.94E+04	0.71	9.981E+06
8	0.8	8.631E+06	8.86E+04	1.03	1.084E+07
9	0.9	7.456E+06	9.63E+04	1.29	1.159E+07
10	1.0	6.655E+06	1.00E+05	1.50	1.225E+07
11	1.1	6.325E+06	9.87E+04	1.56	1.289E+07
12	1.2	5.997E+06	9.59E+04	1.60	1.349E+07
13	1.3	5.527E+06	9.36E+04	1.69	1.404E+07
14	1.4	5.001E+06	9.20E+04	1.84	1.454E+07
15	1.5	4.705E+06	9.11E+04	1.94	1.501E+07
16	1.6	4.588E+06	9.19E+04	2.00	1.547E+07
17	1.7	4.668E+06	9.40E+04	2.01	1.594E+07
18	1.8	5.350E+06	9.65E+04	1.80	1.647E+07
19	1.9	6.790E+06	9.77E+04	1.44	1.715E+07
20	2.0	8.139E+06	9.56E+04	1.17	1.796E+07
21	2.1	8.116E+06	9.03E+04	1.11	1.878E+07
22	2.2	6.514E+06	8.45E+04	1.30	1.943E+07
23	2.3	4.303E+06	8.06E+04	1.84	1.987E+07
24	2.4	2.802E+06	7.92E+04	2.80	2.015E+07
25	2.5	2.117E+06	7.91E+04	3.74	2.036E+07
26	2.6	1.856E+06	7.80E+04	4.20	2.055E+07
27	2.7	1.695E+06	7.60E+04	4.49	2.071E+07
28	2.8	1.350E+06	7.45E+04	4.81	2.087E+07
29	2.9	1.466E+06	7.35E+04	5.01	2.102E+07
30	3.0	1.492E+06	7.29E+04	4.89	2.117E+07
31	3.1	1.364E+06	7.24E+04	4.63	2.132E+07
32	3.2	1.576E+06	7.20E+04	4.57	2.148E+07
33	3.3	1.516E+06	7.19E+04	4.74	2.163E+07
34	3.4	1.399E+06	7.19E+04	5.14	2.177E+07
35	3.5	1.237E+06	7.22E+04	5.83	2.189E+07
36	3.6	1.075E+06	7.28E+04	6.77	2.200E+07
37	3.7	9.538E+05	7.38E+04	7.74	2.210E+07
38	3.8	8.784E+05	7.51E+04	8.54	2.219E+07
39	3.9	8.281E+05	7.65E+04	9.26	2.227E+07
40	4.0	7.842E+05	7.80E+04	9.95	2.235E+07
41	4.1	7.854E+05	7.94E+04	10.11	2.243E+07
42	4.2	8.494E+05	8.04E+04	9.46	2.251E+07
43	4.3	9.360E+05	8.10E+04	8.48	2.261E+07
44	4.4	1.052E+06	8.14E+04	7.74	2.271E+07
45	4.5	1.111E+06	8.16E+04	7.35	2.282E+07
46	4.6	1.139E+06	8.17E+04	7.23	2.293E+07
47	4.7	1.117E+06	8.17E+04	7.32	2.305E+07
48	4.8	1.074E+06	8.17E+04	7.61	2.315E+07
49	4.9	1.009E+06	8.17E+04	8.10	2.325E+07
50	5.0	9.301E+05	8.19E+04	8.80	2.335E+07
51	5.1	8.641E+05	8.17E+04	9.46	2.343E+07
52	5.2	8.183E+05	8.12E+04	9.93	2.352E+07
53	5.3	7.880E+05	8.10E+04	10.27	2.359E+07
54	5.4	7.644E+05	8.07E+04	10.56	2.367E+07
55	5.5	7.339E+05	8.04E+04	10.96	2.374E+07
56	5.6	6.837E+05	8.02E+04	11.73	2.381E+07
57	5.7	6.186E+05	8.02E+04	12.97	2.387E+07
58	5.8	5.567E+05	8.07E+04	14.49	2.393E+07
59	5.9	5.223E+05	8.13E+04	15.57	2.398E+07
60	6.0	5.236E+05	8.21E+04	15.67	2.403E+07
61	6.1	5.474E+05	8.24E+04	15.03	2.409E+07
62	6.2	5.753E+05	8.21E+04	14.27	2.415E+07
63	6.3	5.959E+05	8.14E+04	13.66	2.421E+07
64	6.4	6.153E+05	8.05E+04	13.09	2.427E+07
65	6.5	6.378E+05	7.94E+04	12.45	2.433E+07
66	6.6	6.598E+05	7.80E+04	11.82	2.440E+07
67	6.7	6.751E+05	7.63E+04	11.31	2.447E+07
68	6.8	6.752E+05	7.47E+04	11.06	2.453E+07
69	6.9	6.633E+05	7.30E+04	11.00	2.460E+07
70	7.0	6.489E+05	7.13E+04	10.99	2.466E+07
71	7.1	6.314E+05	6.98E+04	11.06	2.473E+07
72	7.2	6.077E+05	6.89E+04	11.33	2.479E+07
73	7.3	5.739E+05	6.83E+04	11.90	2.485E+07
74	7.4	5.241E+05	6.78E+04	12.93	2.490E+07
75	7.5	4.673E+05	6.70E+04	14.33	2.494E+07
76	7.6	4.136E+05	6.61E+04	15.97	2.499E+07
77	7.7	3.669E+05	6.50E+04	17.71	2.502E+07
78	7.8	3.341E+05	6.41E+04	19.18	2.506E+07
79	7.9	3.096E+05	6.38E+04	20.62	2.509E+07
80	8.0	2.852E+05	6.43E+04	22.54	2.512E+07

D-4: Gamma-ray spectrum at a range of 179m (1981).

GROUP	UPPER ENERGY (MEV)	PARTICLE FLUX (PARTICLES/ CM2 MEV MIN)	ERROR (STD. DEV.)	ERROR (%)	RUNNING INTEGRAL (/CM2 MIN)
4	0.4	3.508E+07	8.14E+04	0.23	3.508E+07
5	0.5	3.273E+07	7.19E+04	0.22	6.781E+07
6	0.6	2.250E+07	7.62E+04	0.34	9.031E+07
7	0.7	1.143E+07	8.13E+04	0.71	1.017E+08
8	0.8	7.927E+06	9.28E+04	1.17	1.096E+08
9	0.9	6.615E+06	1.01E+05	1.52	1.162E+08
10	1.0	5.206E+06	1.05E+05	1.68	1.214E+08
11	1.1	5.908E+06	1.05E+05	1.78	1.292E+08
12	1.2	5.361E+06	1.04E+05	1.95	1.346E+08
13	1.3	4.784E+06	1.03E+05	2.16	1.393E+08
14	1.4	4.562E+06	1.02E+05	2.25	1.439E+08
15	1.5	4.167E+06	1.02E+05	2.44	1.481E+08
16	1.6	3.844E+06	1.05E+05	2.72	1.519E+08
17	1.7	3.605E+06	1.08E+05	3.00	1.555E+08
18	1.8	3.416E+06	1.12E+05	3.28	1.589E+08
19	1.9	3.483E+06	1.16E+05	3.33	1.624E+08
20	2.0	4.060E+06	1.21E+05	2.98	1.665E+08
21	2.1	6.284E+06	1.24E+05	1.97	1.727E+08
22	2.2	9.160E+06	1.23E+05	1.31	1.819E+08
23	2.3	9.271E+06	1.11E+05	1.20	1.912E+08
24	2.4	6.483E+06	1.03E+05	1.59	1.977E+08
25	2.5	3.603E+06	9.96E+04	2.76	2.013E+08
26	2.6	2.065E+06	9.88E+04	4.79	2.033E+08
27	2.7	1.473E+06	9.76E+04	6.62	2.048E+08
28	2.8	1.382E+06	9.58E+04	6.88	2.062E+08
29	2.9	1.491E+06	9.39E+04	6.30	2.077E+08
30	3.0	1.534E+06	9.29E+04	6.05	2.092E+08
31	3.1	1.421E+06	9.29E+04	6.54	2.106E+08
32	3.2	1.191E+06	9.43E+04	7.92	2.118E+08
33	3.3	1.067E+06	9.64E+04	9.21	2.129E+08
34	3.4	1.056E+06	9.87E+04	9.34	2.139E+08
35	3.5	1.211E+06	1.01E+05	8.31	2.151E+08
36	3.6	1.351E+06	1.02E+05	7.55	2.165E+08
37	3.7	1.300E+06	1.03E+05	7.92	2.178E+08
38	3.8	1.107E+06	1.05E+05	9.45	2.189E+08
39	3.9	9.102E+05	1.07E+05	11.75	2.198E+08
40	4.0	7.722E+05	1.10E+05	14.21	2.206E+08
41	4.1	7.467E+05	1.12E+05	15.00	2.213E+08
42	4.2	7.075E+05	1.14E+05	16.12	2.221E+08
43	4.3	7.083E+05	1.15E+05	16.56	2.229E+08
44	4.4	7.006E+05	1.17E+05	16.64	2.236E+08
45	4.5	6.898E+05	1.19E+05	17.24	2.243E+08
46	4.6	7.631E+05	1.21E+05	15.86	2.251E+08
47	4.7	7.903E+05	1.23E+05	15.55	2.259E+08
48	4.8	7.816E+05	1.25E+05	15.98	2.266E+08
49	4.9	8.322E+05	1.27E+05	15.26	2.275E+08
50	5.0	1.012E+06	1.29E+05	12.71	2.285E+08
51	5.1	1.136E+06	1.29E+05	11.31	2.296E+08
52	5.2	1.164E+06	1.28E+05	11.58	2.307E+08
53	5.3	9.460E+05	1.28E+05	13.52	2.317E+08
54	5.4	7.718E+05	1.28E+05	16.65	2.324E+08
55	5.5	6.505E+05	1.29E+05	19.78	2.331E+08
56	5.6	5.757E+05	1.30E+05	22.65	2.337E+08
57	5.7	5.569E+05	1.32E+05	23.62	2.342E+08
58	5.8	5.411E+05	1.33E+05	24.53	2.348E+08
59	5.9	5.347E+05	1.35E+05	25.23	2.353E+08
60	6.0	5.830E+05	1.38E+05	23.64	2.359E+08
61	6.1	6.170E+05	1.40E+05	22.65	2.365E+08
62	6.2	5.877E+05	1.40E+05	24.70	2.371E+08
63	6.3	4.899E+05	1.40E+05	28.58	2.376E+08
64	6.4	4.010E+05	1.40E+05	34.79	2.380E+08
65	6.5	3.342E+05	1.40E+05	41.74	2.383E+08
66	6.6	3.037E+05	1.39E+05	45.83	2.386E+08
67	6.7	2.590E+05	1.39E+05	53.70	2.389E+08
68	6.8	2.388E+05	1.40E+05	58.63	2.391E+08
69	6.9	2.957E+05	1.42E+05	47.93	2.394E+08
70	7.0	4.299E+05	1.42E+05	33.11	2.398E+08
71	7.1	5.685E+05	1.41E+05	24.79	2.404E+08
72	7.2	6.884E+05	1.38E+05	20.09	2.411E+08
73	7.3	7.406E+05	1.36E+05	18.31	2.418E+08
74	7.4	7.229E+05	1.34E+05	18.49	2.425E+08
75	7.5	7.186E+05	1.32E+05	18.28	2.433E+08
76	7.6	6.956E+05	1.29E+05	18.52	2.440E+08
77	7.7	6.772E+05	1.26E+05	18.61	2.446E+08
78	7.8	6.694E+05	1.23E+05	18.37	2.453E+08
79	7.9	6.084E+05	1.20E+05	19.68	2.459E+08
80	8.0	5.212E+05	1.17E+05	22.45	2.464E+08

D-5: Gamma-ray spectrum at a range of 260m (1981).

GROUP	UPPER ENERGY (MEV)	PARTICLE FLUX (PARTICLES/ CM2 MEV MIN)	ERROR (STD. DEV.)	ERROR (%)	RUNNING INTEGRAL (/CM2 MIN)
4	0.4	1.109E+07	2.62E+04	0.24	1.109E+07
5	0.5	1.007E+07	2.36E+04	0.23	2.116E+07
6	0.6	6.570E+06	2.39E+04	0.36	2.773E+07
7	0.7	3.268E+06	2.51E+04	0.77	3.100E+07
8	0.8	2.522E+06	2.88E+04	1.14	3.352E+07
9	0.9	2.157E+06	3.21E+04	1.49	3.568E+07
10	1.0	1.853E+06	3.40E+04	1.84	3.753E+07
11	1.1	1.679E+06	3.42E+04	2.04	3.921E+07
12	1.2	1.562E+06	3.41E+04	2.18	4.077E+07
13	1.3	1.472E+06	3.39E+04	2.31	4.225E+07
14	1.4	1.358E+06	3.38E+04	2.49	4.360E+07
15	1.5	1.289E+06	3.39E+04	2.63	4.489E+07
16	1.6	1.222E+06	3.48E+04	2.85	4.611E+07
17	1.7	1.200E+06	3.60E+04	3.00	4.731E+07
18	1.8	1.214E+06	3.73E+04	3.07	4.853E+07
19	1.9	1.164E+06	3.95E+04	3.35	4.969E+07
20	2.0	1.208E+06	4.11E+04	3.40	5.090E+07
21	2.1	1.783E+06	4.27E+04	2.39	5.268E+07
22	2.2	2.863E+06	4.23E+04	1.48	5.554E+07
23	2.3	3.327E+06	3.93E+04	1.18	5.887E+07
24	2.4	2.573E+06	3.57E+04	1.39	6.144E+07
25	2.5	1.671E+06	3.35E+04	2.00	6.291E+07
26	2.6	1.317E+06	3.27E+04	4.12	6.370E+07
27	2.7	9.436E+05	3.24E+04	5.36	6.425E+07
28	2.8	9.059E+05	3.23E+04	6.19	6.475E+07
29	2.9	9.922E+05	3.23E+04	5.96	6.524E+07
30	3.0	9.946E+05	3.24E+04	6.69	6.573E+07
31	3.1	9.459E+05	3.26E+04	7.31	6.617E+07
32	3.2	9.758E+05	3.31E+04	8.81	6.665E+07
33	3.3	9.309E+05	3.39E+04	10.23	6.708E+07
34	3.4	9.223E+05	3.47E+04	10.77	6.750E+07
35	3.5	9.424E+05	3.56E+04	10.42	6.795E+07
36	3.6	9.024E+05	3.64E+04	9.05	6.835E+07
37	3.7	8.453E+05	3.59E+04	8.29	6.879E+07
38	3.8	9.227E+05	3.74E+04	8.65	6.882E+07
39	3.9	8.805E+05	3.80E+04	10.56	6.918E+07
40	4.0	2.993E+05	3.88E+04	12.95	6.948E+07
41	4.1	2.314E+05	3.93E+04	15.99	6.971E+07
42	4.2	1.882E+05	4.01E+04	21.31	6.990E+07
43	4.3	2.028E+05	4.10E+04	20.21	7.010E+07
44	4.4	2.034E+05	4.18E+04	19.94	7.031E+07
45	4.5	2.123E+05	4.26E+04	20.08	7.052E+07
46	4.6	2.199E+05	4.36E+04	19.82	7.074E+07
47	4.7	2.453E+05	4.44E+04	18.08	7.099E+07
48	4.8	2.791E+05	4.52E+04	16.19	7.126E+07
49	4.9	3.101E+05	4.58E+04	14.78	7.157E+07
50	5.0	3.251E+05	4.64E+04	14.27	7.190E+07
51	5.1	3.247E+05	4.67E+04	14.39	7.222E+07
52	5.2	3.189E+05	4.70E+04	14.73	7.254E+07
53	5.3	3.153E+05	4.72E+04	14.96	7.286E+07
54	5.4	3.044E+05	4.73E+04	15.55	7.316E+07
55	5.5	2.754E+05	4.76E+04	17.27	7.344E+07
56	5.6	2.562E+05	4.79E+04	18.69	7.369E+07
57	5.7	2.391E+05	4.82E+04	20.17	7.393E+07
58	5.8	2.372E+05	4.86E+04	20.50	7.417E+07
59	5.9	2.312E+05	4.91E+04	21.23	7.440E+07
60	6.0	2.229E+05	4.96E+04	22.25	7.462E+07
61	6.1	2.042E+05	5.00E+04	24.50	7.483E+07
62	6.2	1.885E+05	5.02E+04	26.61	7.502E+07
63	6.3	1.676E+05	5.01E+04	29.89	7.519E+07
64	6.4	1.451E+05	5.01E+04	34.53	7.533E+07
65	6.5	1.322E+05	5.02E+04	37.97	7.546E+07
66	6.6	1.150E+05	5.03E+04	43.74	7.558E+07
67	6.7	1.048E+05	5.03E+04	48.01	7.568E+07
68	6.8	0.913E+04	5.03E+04	55.48	7.577E+07
69	6.9	7.505E+04	5.06E+04	67.38	7.585E+07
70	7.0	7.933E+04	5.10E+04	64.27	7.593E+07
71	7.1	1.013E+05	5.12E+04	50.59	7.603E+07
72	7.2	1.444E+05	5.12E+04	35.44	7.617E+07
73	7.3	1.834E+05	5.05E+04	27.74	7.636E+07
74	7.4	2.158E+05	5.05E+04	23.42	7.657E+07
75	7.5	2.305E+05	5.02E+04	21.79	7.680E+07
76	7.6	2.183E+05	5.01E+04	22.89	7.702E+07
77	7.7	2.126E+05	5.00E+04	23.51	7.723E+07
78	7.8	2.051E+05	4.97E+04	24.23	7.744E+07
79	7.9	1.897E+05	4.90E+04	25.81	7.763E+07
80	8.0	1.763E+05	4.78E+04	27.18	7.780E+07

D-6: Gamma-ray spectrum at a range of 300m (1980).

GROUP	UPPER ENERGY (MEV)	PARTICLE FLUX (PARTICLES/ CM2-MEV-RAM)	ERROR (STD. DEV.)	ERROR (%)	RUNNING INTEGRAL (/CM2-RAM)
4	0.4	7.722E+08	2.11E+04	0.27	7.722E+09
5	0.5	6.393E+08	1.44E+04	0.23	1.411E+09
6	0.6	3.830E+08	1.44E+04	0.38	1.794E+09
7	0.7	2.167E+08	1.52E+04	0.71	2.010E+09
8	0.8	1.995E+08	1.72E+04	1.08	2.165E+09
9	0.9	1.308E+08	1.85E+04	1.41	2.302E+09
10	1.0	1.204E+08	1.95E+04	1.65	2.423E+09
11	1.1	1.101E+08	1.98E+04	1.68	2.541E+09
12	1.2	1.135E+08	1.88E+04	1.71	2.655E+09
13	1.3	1.068E+08	1.91E+04	1.79	2.761E+09
14	1.4	9.996E+07	1.89E+04	1.89	2.861E+09
15	1.5	9.559E+07	1.85E+04	1.98	2.957E+09
16	1.6	9.428E+07	1.93E+04	2.05	3.051E+09
17	1.7	9.724E+07	1.99E+04	2.09	3.148E+09
18	1.8	1.191E+08	2.07E+04	1.78	3.267E+09
19	1.9	1.559E+08	2.11E+04	1.35	3.423E+09
20	2.0	1.965E+08	2.07E+04	1.05	3.619E+09
21	2.1	2.000E+08	1.94E+04	0.97	3.819E+09
22	2.2	1.820E+08	1.86E+04	1.11	3.979E+09
23	2.3	1.102E+08	1.70E+04	1.54	4.089E+09
24	2.4	7.056E+07	1.67E+04	2.35	4.159E+09
25	2.5	4.925E+07	1.65E+04	3.36	4.209E+09
26	2.6	4.034E+07	1.63E+04	4.03	4.249E+09
27	2.7	3.657E+07	1.58E+04	4.33	4.285E+09
28	2.8	3.371E+07	1.55E+04	4.59	4.319E+09
29	2.9	3.129E+07	1.52E+04	4.86	4.350E+09
30	3.0	3.061E+07	1.51E+04	4.94	4.381E+09
31	3.1	3.102E+07	1.51E+04	4.86	4.411E+09
32	3.2	3.123E+07	1.51E+04	4.82	4.443E+09
33	3.3	3.025E+07	1.51E+04	4.98	4.473E+09
34	3.4	2.749E+07	1.51E+04	5.49	4.500E+09
35	3.5	2.377E+07	1.52E+04	6.40	4.524E+09
36	3.6	2.086E+07	1.54E+04	7.38	4.545E+09
37	3.7	1.914E+07	1.57E+04	8.19	4.564E+09
38	3.8	1.755E+07	1.60E+04	9.09	4.582E+09
39	3.9	1.607E+07	1.63E+04	10.17	4.598E+09
40	4.0	1.580E+07	1.67E+04	10.73	4.614E+09
41	4.1	1.672E+07	1.71E+04	10.20	4.630E+09
42	4.2	1.806E+07	1.73E+04	9.56	4.648E+09
43	4.3	2.140E+07	1.76E+04	8.19	4.670E+09
44	4.4	2.365E+07	1.75E+04	7.40	4.694E+09
45	4.5	2.522E+07	1.75E+04	6.98	4.719E+09
46	4.6	2.583E+07	1.78E+04	6.89	4.745E+09
47	4.7	2.590E+07	1.76E+04	6.82	4.771E+09
48	4.8	2.543E+07	1.76E+04	6.93	4.796E+09
49	4.9	2.483E+07	1.78E+04	7.11	4.821E+09
50	5.0	2.359E+07	1.78E+04	7.47	4.845E+09
51	5.1	2.146E+07	1.75E+04	8.17	4.866E+09
52	5.2	1.884E+07	1.74E+04	9.24	4.885E+09
53	5.3	1.695E+07	1.74E+04	10.48	4.902E+09
54	5.4	1.520E+07	1.74E+04	11.43	4.917E+09
55	5.5	1.479E+07	1.74E+04	11.77	4.932E+09
56	5.6	1.489E+07	1.74E+04	11.71	4.946E+09
57	5.7	1.511E+07	1.74E+04	11.54	4.962E+09
58	5.8	1.509E+07	1.74E+04	11.55	4.977E+09
59	5.9	1.470E+07	1.74E+04	11.88	4.991E+09
60	6.0	1.387E+07	1.74E+04	12.58	5.005E+09
61	6.1	1.282E+07	1.75E+04	13.64	5.018E+09
62	6.2	1.193E+07	1.75E+04	14.70	5.030E+09
63	6.3	1.140E+07	1.76E+04	15.41	5.041E+09
64	6.4	1.122E+07	1.75E+04	15.60	5.052E+09
65	6.5	1.121E+07	1.73E+04	15.49	5.064E+09
66	6.6	1.142E+07	1.71E+04	15.00	5.075E+09
67	6.7	1.206E+07	1.70E+04	14.08	5.087E+09
68	6.8	1.322E+07	1.67E+04	12.67	5.100E+09
69	6.9	1.464E+07	1.64E+04	11.23	5.115E+09
70	7.0	1.582E+07	1.60E+04	10.11	5.131E+09
71	7.1	1.636E+07	1.55E+04	9.50	5.147E+09
72	7.2	1.601E+07	1.51E+04	9.48	5.163E+09
73	7.3	1.501E+07	1.48E+04	9.87	5.178E+09
74	7.4	1.372E+07	1.46E+04	10.63	5.192E+09
75	7.5	1.237E+07	1.44E+04	11.65	5.204E+09
76	7.6	1.117E+07	1.43E+04	12.80	5.216E+09
77	7.7	1.022E+07	1.42E+04	13.92	5.226E+09
78	7.8	9.610E+06	1.42E+04	14.81	5.235E+09
79	7.9	9.029E+06	1.43E+04	15.90	5.243E+09
80	8.0	8.778E+06	1.43E+04	21.05	5.249E+09

D-7: Gamma-ray spectrum at a range of 400m (1981).

GROUP	UPPER ENERGY (MEV)	PARTICLE FLUX (PARTICLES/ CM2-MEV-RAM)	ERROR (STD. DEV.)	ERROR (%)	RUNNING INTEGRAL (/CM2-RAM)
4	0.4	2.801E+08	5.68E+03	0.20	2.801E+09
5	0.5	2.362E+08	3.88E+03	0.16	5.163E+09
6	0.6	1.478E+08	3.83E+03	0.26	6.641E+09
7	0.7	7.853E+07	3.99E+03	0.51	7.430E+09
8	0.8	5.600E+07	4.50E+03	0.80	7.990E+09
9	0.9	4.670E+07	4.96E+03	1.06	8.457E+09
10	1.0	4.201E+07	5.22E+03	1.24	8.878E+09
11	1.1	4.023E+07	5.20E+03	1.29	9.280E+09
12	1.2	3.812E+07	5.13E+03	1.35	9.661E+09
13	1.3	3.626E+07	5.07E+03	1.40	1.002E+10
14	1.4	3.465E+07	5.02E+03	1.45	1.037E+10
15	1.5	3.299E+07	5.02E+03	1.52	1.070E+10
16	1.6	3.270E+07	5.13E+03	1.57	1.103E+10
17	1.7	3.326E+07	5.27E+03	1.59	1.136E+10
18	1.8	3.467E+07	5.48E+03	1.57	1.171E+10
19	1.9	4.155E+07	5.66E+03	1.36	1.212E+10
20	2.0	5.592E+07	5.74E+03	1.03	1.268E+10
21	2.1	6.708E+07	5.57E+03	0.82	1.336E+10
22	2.2	6.573E+07	5.22E+03	0.79	1.402E+10
23	2.3	5.053E+07	4.90E+03	0.97	1.452E+10
24	2.4	3.307E+07	4.71E+03	1.42	1.485E+10
25	2.5	2.149E+07	4.63E+03	2.16	1.507E+10
26	2.6	1.625E+07	4.58E+03	2.82	1.523E+10
27	2.7	1.411E+07	4.47E+03	3.17	1.537E+10
28	2.8	1.289E+07	4.38E+03	3.40	1.550E+10
29	2.9	1.181E+07	4.32E+03	3.66	1.562E+10
30	3.0	1.091E+07	4.29E+03	3.94	1.573E+10
31	3.1	1.056E+07	4.30E+03	4.08	1.583E+10
32	3.2	1.078E+07	4.33E+03	4.02	1.594E+10
33	3.3	1.123E+07	4.36E+03	3.88	1.605E+10
34	3.4	1.135E+07	4.38E+03	3.86	1.617E+10
35	3.5	1.095E+07	4.41E+03	4.03	1.628E+10
36	3.6	9.969E+06	4.44E+03	4.46	1.638E+10
37	3.7	8.653E+06	4.50E+03	5.20	1.646E+10
38	3.8	7.373E+06	4.58E+03	6.21	1.654E+10
39	3.9	6.349E+06	4.69E+03	7.38	1.660E+10
40	4.0	5.782E+06	4.80E+03	8.33	1.666E+10
41	4.1	5.861E+06	4.90E+03	8.37	1.672E+10
42	4.2	6.646E+06	4.98E+03	7.49	1.678E+10
43	4.3	7.704E+06	5.03E+03	6.53	1.686E+10
44	4.4	8.595E+06	5.07E+03	5.90	1.694E+10
45	4.5	9.116E+06	5.11E+03	5.60	1.704E+10
46	4.6	9.399E+06	5.15E+03	5.47	1.713E+10
47	4.7	9.530E+06	5.19E+03	5.40	1.723E+10
48	4.8	9.826E+06	5.21E+03	5.31	1.732E+10
49	4.9	1.009E+07	5.24E+03	5.20	1.742E+10
50	5.0	1.031E+07	5.25E+03	5.09	1.753E+10
51	5.1	1.036E+07	5.22E+03	5.04	1.763E+10
52	5.2	1.009E+07	5.16E+03	5.15	1.773E+10
53	5.3	9.115E+06	5.10E+03	5.59	1.782E+10
54	5.4	7.966E+06	5.05E+03	6.47	1.790E+10
55	5.5	6.422E+06	5.04E+03	7.85	1.797E+10
56	5.6	5.398E+06	5.06E+03	9.37	1.802E+10
57	5.7	4.964E+06	5.10E+03	10.27	1.807E+10
58	5.8	5.081E+06	5.14E+03	10.11	1.812E+10
59	5.9	5.479E+06	5.17E+03	9.44	1.817E+10
60	6.0	5.840E+06	5.20E+03	8.90	1.823E+10
61	6.1	5.988E+06	5.20E+03	8.68	1.829E+10
62	6.2	5.855E+06	5.18E+03	8.84	1.835E+10
63	6.3	5.509E+06	5.13E+03	9.31	1.841E+10
64	6.4	5.020E+06	5.07E+03	10.10	1.846E+10
65	6.5	4.499E+06	5.00E+03	11.12	1.850E+10
66	6.6	4.074E+06	4.95E+03	12.14	1.854E+10
67	6.7	3.861E+06	4.90E+03	12.70	1.858E+10
68	6.8	3.845E+06	4.87E+03	12.35	1.862E+10
69	6.9	4.294E+06	4.84E+03	11.28	1.866E+10
70	7.0	4.773E+06	4.84E+03	10.05	1.871E+10
71	7.1	5.223E+06	4.73E+03	9.06	1.876E+10
72	7.2	5.490E+06	4.63E+03	8.48	1.882E+10
73	7.3	5.533E+06	4.58E+03	8.27	1.887E+10
74	7.4	5.403E+06	4.50E+03	8.32	1.893E+10
75	7.5	5.135E+06	4.42E+03	8.61	1.898E+10
76	7.6	4.830E+06	4.35E+03	9.00	1.903E+10
77	7.7	4.555E+06	4.30E+03	9.44	1.907E+10
78	7.8	4.318E+06	4.27E+03	9.89	1.911E+10
79	7.9	4.140E+06	4.25E+03	10.27	1.916E+10
80	8.0	3.950E+06	4.23E+03	10.72	1.920E+10

D-8: Gamma-ray spectrum at a range of 1080m (1980).

GROUP	UPPER ENERGY (MEV)	PARTICLE FLUX (PARTICLES/ CM2-MEV-RAH)	ERROR (STD. DEV.)	ERROR (%)	RUNNING INTEGRAL (/CM2-RAH)
4	0.4	1.953E+04	1.31E+02	0.67	1.953E+03
5	0.5	1.530E+04	9.11E+01	0.60	3.483E+03
6	0.6	1.009E+04	9.71E+01	0.96	4.492E+03
7	0.7	6.018E+03	1.04E+02	1.72	5.094E+03
8	0.8	4.334E+03	1.15E+02	2.65	5.527E+03
9	0.9	3.693E+03	1.23E+02	3.33	5.897E+03
10	1.0	3.169E+03	1.24E+02	3.92	6.214E+03
11	1.1	3.080E+03	1.19E+02	3.87	6.522E+03
12	1.2	3.145E+03	1.17E+02	3.71	6.836E+03
13	1.3	2.816E+03	1.15E+02	4.08	7.118E+03
14	1.4	2.655E+03	1.08E+02	4.41	7.383E+03
15	1.5	2.256E+03	1.01E+02	4.46	7.589E+03
16	1.6	2.209E+03	9.68E+01	4.38	7.810E+03
17	1.7	2.178E+03	9.53E+01	4.38	8.028E+03
18	1.8	2.179E+03	9.42E+01	4.32	8.245E+03
19	1.9	2.040E+03	9.39E+01	3.80	8.486E+03
20	2.0	2.708E+03	9.45E+01	3.49	8.757E+03
21	2.1	2.804E+03	9.45E+01	3.37	9.037E+03
22	2.2	2.658E+03	9.41E+01	3.54	9.303E+03
23	2.3	2.276E+03	9.44E+01	4.15	9.531E+03
24	2.4	1.761E+03	9.48E+01	5.38	9.707E+03
25	2.5	1.345E+03	9.38E+01	6.97	9.842E+03
26	2.6	1.159E+03	8.95E+01	7.72	9.957E+03
27	2.7	1.080E+03	8.47E+01	7.84	1.007E+04
28	2.8	9.721E+02	8.17E+01	8.41	1.016E+04
29	2.9	8.799E+02	7.95E+01	9.03	1.025E+04
30	3.0	8.583E+02	7.81E+01	9.10	1.034E+04
31	3.1	8.788E+02	7.77E+01	8.84	1.042E+04
32	3.2	9.402E+02	7.80E+01	8.30	1.052E+04
33	3.3	1.014E+03	7.86E+01	7.74	1.062E+04
34	3.4	1.022E+03	7.89E+01	7.72	1.072E+04
35	3.5	9.453E+02	7.94E+01	8.40	1.082E+04
36	3.6	8.385E+02	8.09E+01	9.64	1.090E+04
37	3.7	7.946E+02	8.35E+01	11.07	1.098E+04
38	3.8	7.024E+02	8.68E+01	12.36	1.105E+04
39	3.9	6.700E+02	9.07E+01	13.53	1.111E+04
40	4.0	6.564E+02	9.53E+01	14.52	1.118E+04
41	4.1	6.565E+02	9.89E+01	15.06	1.124E+04
42	4.2	6.830E+02	1.00E+02	14.65	1.131E+04
43	4.3	7.500E+02	1.00E+02	13.37	1.139E+04
44	4.4	8.444E+02	1.01E+02	11.93	1.147E+04
45	4.5	9.406E+02	1.01E+02	10.78	1.157E+04
46	4.6	1.031E+03	1.02E+02	9.91	1.167E+04
47	4.7	1.089E+03	1.04E+02	9.50	1.178E+04
48	4.8	1.130E+03	1.09E+02	9.61	1.189E+04
49	4.9	1.130E+03	1.13E+02	10.02	1.201E+04
50	5.0	1.139E+03	1.16E+02	10.15	1.212E+04
51	5.1	1.127E+03	1.15E+02	9.79	1.224E+04
52	5.2	1.198E+03	1.13E+02	9.45	1.236E+04
53	5.3	1.168E+03	1.13E+02	9.70	1.247E+04
54	5.4	1.065E+03	1.15E+02	10.78	1.258E+04
55	5.5	9.027E+02	1.17E+02	12.91	1.267E+04
56	5.6	7.069E+02	1.18E+02	16.64	1.274E+04
57	5.7	5.153E+02	1.17E+02	22.77	1.279E+04
58	5.8	3.654E+02	1.17E+02	32.05	1.283E+04
59	5.9	2.810E+02	1.19E+02	42.23	1.286E+04
60	6.0	2.544E+02	1.22E+02	47.93	1.288E+04
61	6.1	2.614E+02	1.26E+02	48.09	1.291E+04
62	6.2	2.805E+02	1.29E+02	45.93	1.294E+04
63	6.3	3.090E+02	1.31E+02	42.47	1.297E+04
64	6.4	3.538E+02	1.35E+02	38.04	1.300E+04
65	6.5	4.108E+02	1.41E+02	34.28	1.304E+04
66	6.6	4.670E+02	1.50E+02	32.09	1.309E+04
67	6.7	4.987E+02	1.60E+02	32.05	1.314E+04
68	6.8	4.937E+02	1.69E+02	34.31	1.319E+04
69	6.9	4.556E+02	1.80E+02	39.42	1.323E+04
70	7.0	4.009E+02	1.91E+02	47.75	1.327E+04
71	7.1	3.526E+02	2.04E+02	57.75	1.331E+04
72	7.2	3.199E+02	2.14E+02	66.87	1.334E+04
73	7.3	2.996E+02	2.21E+02	73.80	1.337E+04
74	7.4	2.788E+02	2.28E+02	81.68	1.340E+04
75	7.5	2.435E+02	2.39E+02	98.30	1.342E+04
76	7.6	1.922E+02	2.42E+02	125.81	1.344E+04
77	7.7	1.339E+02	2.48E+02	186.15	1.346E+04
78	7.8	7.072E+01	2.56E+02	324.50	1.346E+04
79	7.9	3.838E+01	2.83E+02	688.81	1.347E+04
80	8.0	1.478E+01	2.77E+02	1874.81	1.347E+04

D-9: Gamma-ray spectrum at a range of 1080m (1981).

GROUP	UPPER ENERGY (MEV)	PARTICLE FLUX (PARTICLES/ CM2-MEV-RAH)	ERROR (STD. DEV.)	ERROR (%)	RUNNING INTEGRAL (/CM2-RAH)
4	0.4	2.002E+04	1.28E+02	0.64	2.002E+03
5	0.5	1.614E+04	9.77E+01	0.56	3.617E+03
6	0.6	1.110E+04	9.19E+01	0.83	4.727E+03
7	0.7	6.866E+03	9.63E+01	1.40	5.413E+03
8	0.8	4.907E+03	1.07E+02	2.17	5.904E+03
9	0.9	4.054E+03	1.14E+02	2.80	6.309E+03
10	1.0	3.750E+03	1.14E+02	3.05	6.684E+03
11	1.1	3.409E+03	1.13E+02	3.32	7.025E+03
12	1.2	2.971E+03	1.12E+02	3.78	7.322E+03
13	1.3	2.665E+03	1.08E+02	4.07	7.589E+03
14	1.4	2.595E+03	1.00E+02	3.85	7.848E+03
15	1.5	2.307E+03	9.11E+01	3.63	8.079E+03
16	1.6	2.403E+03	8.64E+01	3.55	8.342E+03
17	1.7	2.328E+03	8.61E+01	3.70	8.575E+03
18	1.8	2.186E+03	8.75E+01	4.00	8.793E+03
19	1.9	2.142E+03	8.98E+01	4.19	9.008E+03
20	2.0	2.329E+03	9.29E+01	3.99	9.240E+03
21	2.1	2.766E+03	9.43E+01	3.41	9.517E+03
22	2.2	3.034E+03	9.45E+01	3.11	9.821E+03
23	2.3	2.679E+03	9.56E+01	3.58	1.009E+04
24	2.4	1.877E+03	9.57E+01	5.10	1.028E+04
25	2.5	1.291E+03	9.34E+01	7.24	1.040E+04
26	2.6	1.130E+03	8.87E+01	7.86	1.052E+04
27	2.7	1.092E+03	8.27E+01	7.57	1.063E+04
28	2.8	1.021E+03	7.77E+01	7.61	1.073E+04
29	2.9	9.941E+02	7.95E+01	7.92	1.082E+04
30	3.0	8.951E+02	7.52E+01	8.41	1.091E+04
31	3.1	8.522E+02	7.50E+01	8.80	1.100E+04
32	3.2	8.512E+02	7.74E+01	9.09	1.108E+04
33	3.3	8.963E+02	7.98E+01	8.89	1.117E+04
34	3.4	9.691E+02	8.17E+01	8.43	1.127E+04
35	3.5	1.017E+03	8.33E+01	8.20	1.137E+04
36	3.6	9.968E+02	8.92E+01	8.95	1.147E+04
37	3.7	9.182E+02	8.73E+01	9.51	1.156E+04
38	3.8	8.250E+02	8.92E+01	10.81	1.165E+04
39	3.9	7.330E+02	9.16E+01	12.50	1.172E+04
40	4.0	6.260E+02	9.44E+01	15.09	1.178E+04
41	4.1	5.106E+02	9.70E+01	19.00	1.183E+04
42	4.2	4.412E+02	9.94E+01	22.52	1.188E+04
43	4.3	4.672E+02	1.02E+02	21.74	1.192E+04
44	4.4	5.853E+02	1.04E+02	17.73	1.198E+04
45	4.5	7.363E+02	1.06E+02	14.36	1.206E+04
46	4.6	8.513E+02	1.07E+02	12.62	1.214E+04
47	4.7	9.013E+02	1.09E+02	12.09	1.223E+04
48	4.8	9.043E+02	1.11E+02	12.24	1.232E+04
49	4.9	9.140E+02	1.12E+02	12.26	1.241E+04
50	5.0	9.901E+02	1.14E+02	11.62	1.251E+04
51	5.1	1.146E+03	1.15E+02	10.46	1.262E+04
52	5.2	1.243E+03	1.17E+02	9.43	1.275E+04
53	5.3	1.333E+03	1.18E+02	8.87	1.288E+04
54	5.4	1.335E+03	1.18E+02	8.84	1.301E+04
55	5.5	1.230E+03	1.17E+02	9.47	1.314E+04
56	5.6	1.061E+03	1.18E+02	11.09	1.324E+04
57	5.7	8.418E+02	1.20E+02	14.27	1.333E+04
58	5.8	6.335E+02	1.24E+02	19.52	1.339E+04
59	5.9	4.765E+02	1.27E+02	26.70	1.344E+04
60	6.0	3.894E+02	1.30E+02	33.40	1.348E+04
61	6.1	3.603E+02	1.34E+02	36.32	1.351E+04
62	6.2	3.894E+02	1.38E+02	35.47	1.355E+04
63	6.3	4.260E+02	1.47E+02	34.43	1.360E+04
64	6.4	4.477E+02	1.58E+02	34.99	1.364E+04
65	6.5	4.334E+02	1.67E+02	37.94	1.368E+04
66	6.6	3.992E+02	1.78E+02	44.09	1.372E+04
67	6.7	3.334E+02	1.83E+02	55.01	1.376E+04
68	6.8	2.647E+02	1.94E+02	73.38	1.378E+04
69	6.9	1.975E+02	2.04E+02	103.08	1.380E+04
70	7.0	1.463E+02	2.12E+02	144.81	1.382E+04
71	7.1	1.188E+02	2.17E+02	183.02	1.383E+04
72	7.2	1.126E+02	2.22E+02	197.27	1.384E+04
73	7.3	1.193E+02	2.28E+02	191.28	1.385E+04
74	7.4	1.257E+02	2.37E+02	187.22	1.387E+04
75	7.5	1.214E+02	2.48E+02	204.30	1.388E+04
76	7.6	1.043E+02	2.58E+02	247.13	1.389E+04
77	7.7	8.884E+01	2.65E+02	298.04	1.390E+04
78	7.8	8.608E+01	2.68E+02	301.92	1.391E+04
79	7.9	1.186E+02	2.70E+02	227.42	1.392E+04
80	8.0	1.744E+02	2.71E+02	155.45	1.394E+04

D-10: Gamma-ray spectrum at a range of 1080m (1982).

GROUP	UPPER ENERGY (MEV)	PARTICLE FLUX (PARTICLES/ CM2-MEV-MIN)	ERROR (STD. DEV.)	ERROR (%)	RUNNING INTEGRAL (/CM2-MIN)
4	0.4	2.140E+04	9.39E+01	0.44	2.140E+03
5	0.5	1.697E+04	6.49E+01	0.38	3.837E+03
6	0.6	1.201E+04	6.84E+01	0.57	5.037E+03
7	0.7	7.588E+03	7.15E+01	0.94	5.796E+03
8	0.8	5.702E+03	7.80E+01	1.37	6.366E+03
9	0.9	4.751E+03	8.32E+01	1.75	6.841E+03
10	1.0	4.207E+03	8.40E+01	2.00	7.262E+03
11	1.1	3.773E+03	8.22E+01	2.18	7.639E+03
12	1.2	3.398E+03	8.04E+01	2.37	7.979E+03
13	1.3	3.139E+03	7.80E+01	2.48	8.292E+03
14	1.4	2.923E+03	7.35E+01	2.51	8.585E+03
15	1.5	2.688E+03	6.84E+01	2.54	8.853E+03
16	1.6	2.584E+03	6.60E+01	2.56	9.112E+03
17	1.7	2.511E+03	6.59E+01	2.62	9.363E+03
18	1.8	2.338E+03	6.64E+01	2.84	9.597E+03
19	1.9	2.218E+03	6.77E+01	3.05	9.819E+03
20	2.0	2.335E+03	6.97E+01	2.99	1.005E+04
21	2.1	2.688E+03	7.09E+01	2.64	1.032E+04
22	2.2	2.903E+03	7.07E+01	2.44	1.061E+04
23	2.3	2.644E+03	7.02E+01	2.65	1.088E+04
24	2.4	2.069E+03	7.05E+01	3.41	1.109E+04
25	2.5	1.553E+03	7.06E+01	4.54	1.124E+04
26	2.6	1.274E+03	6.87E+01	5.38	1.136E+04
27	2.7	1.166E+03	6.55E+01	5.62	1.148E+04
28	2.8	1.095E+03	6.26E+01	5.71	1.159E+04
29	2.9	9.943E+02	6.07E+01	6.10	1.169E+04
30	3.0	9.089E+02	6.04E+01	6.64	1.178E+04
31	3.1	9.026E+02	6.12E+01	6.78	1.187E+04
32	3.2	9.344E+02	6.23E+01	6.66	1.197E+04
33	3.3	9.285E+02	6.32E+01	6.80	1.206E+04
34	3.4	8.999E+02	6.40E+01	7.11	1.215E+04
35	3.5	8.973E+02	6.45E+01	7.19	1.224E+04
36	3.6	9.187E+02	6.48E+01	7.06	1.233E+04
37	3.7	9.179E+02	6.57E+01	7.16	1.242E+04
38	3.8	8.934E+02	6.77E+01	7.83	1.251E+04
39	3.9	7.304E+02	7.04E+01	9.63	1.258E+04
40	4.0	6.514E+02	7.32E+01	12.16	1.264E+04
41	4.1	5.245E+02	7.54E+01	14.37	1.269E+04
42	4.2	5.250E+02	7.68E+01	14.61	1.274E+04
43	4.3	6.025E+02	7.82E+01	12.97	1.281E+04
44	4.4	7.285E+02	7.98E+01	10.96	1.288E+04
45	4.5	8.532E+02	8.20E+01	9.61	1.296E+04
46	4.6	9.514E+02	8.41E+01	8.84	1.306E+04
47	4.7	1.017E+03	8.54E+01	8.40	1.316E+04
48	4.8	1.063E+03	8.60E+01	8.09	1.327E+04
49	4.9	1.079E+03	8.70E+01	8.07	1.337E+04
50	5.0	1.079E+03	8.90E+01	8.23	1.348E+04
51	5.1	1.103E+03	9.05E+01	8.20	1.359E+04
52	5.2	1.187E+03	9.13E+01	7.70	1.371E+04
53	5.3	1.311E+03	9.18E+01	7.06	1.384E+04
54	5.4	1.379E+03	9.24E+01	6.70	1.398E+04
55	5.5	1.366E+03	9.32E+01	6.82	1.412E+04
56	5.6	1.242E+03	9.43E+01	7.59	1.424E+04
57	5.7	1.043E+03	9.53E+01	9.13	1.434E+04
58	5.8	8.103E+02	9.70E+01	11.96	1.443E+04
59	5.9	6.215E+02	9.96E+01	16.02	1.449E+04
60	6.0	4.908E+02	1.01E+02	20.57	1.454E+04
61	6.1	4.359E+02	1.02E+02	23.45	1.458E+04
62	6.2	4.340E+02	1.04E+02	23.87	1.462E+04
63	6.3	4.447E+02	1.05E+02	23.69	1.467E+04
64	6.4	4.293E+02	1.08E+02	25.13	1.471E+04
65	6.5	3.733E+02	1.11E+02	29.72	1.475E+04
66	6.6	2.937E+02	1.15E+02	39.07	1.478E+04
67	6.7	2.190E+02	1.19E+02	54.20	1.480E+04
68	6.8	1.711E+02	1.23E+02	72.01	1.482E+04
69	6.9	1.512E+02	1.28E+02	84.69	1.483E+04
70	7.0	1.463E+02	1.34E+02	91.52	1.485E+04
71	7.1	1.432E+02	1.41E+02	98.12	1.486E+04
72	7.2	1.439E+02	1.47E+02	102.08	1.488E+04
73	7.3	1.627E+02	1.52E+02	93.83	1.489E+04
74	7.4	2.162E+02	1.57E+02	72.56	1.491E+04
75	7.5	3.021E+02	1.60E+02	53.09	1.494E+04
76	7.6	3.943E+02	1.63E+02	41.27	1.498E+04
77	7.7	4.603E+02	1.66E+02	36.04	1.503E+04
78	7.8	4.675E+02	1.71E+02	36.63	1.508E+04
79	7.9	4.111E+02	1.78E+02	43.38	1.512E+04
80	8.0	3.143E+02	1.88E+02	59.82	1.515E+04

APPENDIX E
NEUTRON SPECTRA IN 37-GROUP FORMAT

APPENDIX E: NEUTRON SPECTRA IN 37-GROUP FORMAT

The neutron spectra listed in Appendix C are tabulated herein after regrouping into the DLC-31 (DNA) data library structure, which includes thirty-seven neutron groups with the following energy limits:

GROUP	UPPER ENERGY
1	19.64 MeV
2	16.90 "
3	14.92 "
4	14.19 "
5	13.84 "
6	12.84 "
7	12.21 "
8	11.05 "
9	10.00 "
10	9.048 "
11	8.187 "
12	7.408 "
13	6.376 "
14	4.965 "
15	4.724 "
16	4.066 "
17	3.012 "
18	2.385 "
19	2.307 "

GROUP	UPPER ENERGY
20	1.827 MeV
21	1.108 "
22	550.2 keV
23	157.6 "
24	111.1 "
25	52.48 "
26	24.79 "
27	21.88 "
28	10.33 "
29	3.335 "
30	1.234 "
31	582.9 eV
32	101.3 "
33	29.02 "
34	10.68 "
35	3.059 "
36	1.125 "
37	0.414 "
	1.0E-5 "

The data are tabulated in two columns; the first corresponding to groupwise fluence with units of "neutrons per cm^2.kWh" and the second representing the mean of $E\phi(E)$ within each group, again with units of "neutrons per cm^2.kWh". This latter quantity has been determined according to:

$$\langle E\phi(E)\rangle_j = \frac{\phi_j}{\ln\left(\frac{E_j}{E_{j-1}}\right)}$$

where ϕ_j is the group fluence between energies E_{j-1} and E_j.

E-1: Neutron Spectrum at a range of 15 meters (1980).

GROUP	PARTICLES/CM2-RAH	E * PHI (E)
1		
2		
3		
4		
5		
6		
7		
8		
9	7.6855E+06	7.7084E+07
10	1.0822E+07	1.0638E+08
11	2.0224E+07	2.0207E+08
12	3.9818E+07	2.6605E+08
13	1.3362E+08	9.3501E+08
14	4.1704E+07	8.0834E+08
15	1.4496E+08	9.7836E+08
16	3.7716E+08	1.2501E+09
17	3.8030E+08	1.6486E+09
18	6.9352E+07	1.5185E+09
19	4.4098E+08	1.6815E+09
20	8.4808E+08	1.8963E+09
21	1.2959E+08	2.1065E+09
22	1.8014E+08	1.5244E+09
23	6.4590E+08	1.2625E+09
24	8.3333E+08	1.1130E+09
25	7.0158E+08	9.3598E+08
26	1.0500E+08	8.4499E+08
27	9.7858E+08	7.8402E+08
28	8.9207E+08	6.1617E+08
29	4.7571E+08	4.8226E+08
30	3.6230E+08	3.8369E+08
31	3.1732E+08	2.9597E+08
32	2.8036E+08	2.0865E+08
33	1.8629E+08	1.6776E+08
34	1.5538E+08	1.2612E+08
35	8.9234E+07	8.5598E+07
36	7.8178E+07	7.5867E+07
37	5.7043E+08	5.3654E+07

E-2: Neutron Spectrum at a range of 100 meters (1980).

GROUP	PARTICLES/CM2-RAH	E * PHI (E)
1		
2		
3		
4		
5		
6		
7		
8		
9	9.1065E+04	9.1229E+05
10	1.6953E+05	1.6978E+06
11	2.3474E+05	2.3455E+06
12	5.6462E+05	3.7728E+06
13	2.0448E+06	8.1874E+06
14	6.1858E+05	1.2045E+07
15	2.0092E+06	1.3560E+07
16	5.2415E+06	1.7373E+07
17	6.0865E+06	2.6369E+07
18	1.1004E+06	3.2322E+07
19	7.4445E+06	3.1960E+07
20	1.5321E+07	3.0645E+07
21	2.3178E+07	3.7676E+07
22	3.8393E+07	3.3781E+07
23	9.9153E+06	2.8083E+07
24	1.9795E+07	2.6305E+07
25	1.8173E+07	2.4231E+07
26	2.8864E+06	2.3050E+07
27	1.6546E+07	2.1834E+07
28	2.2151E+07	1.9721E+07
29	1.7243E+07	1.7491E+07
30	1.2155E+07	1.5828E+07
31	2.4014E+07	1.3738E+07
32	1.4448E+07	1.1579E+07
33	1.0159E+07	1.0169E+07
34	1.1228E+07	8.8695E+06
35	7.8614E+06	7.8814E+06
36	7.0725E+06	7.0436E+06
37	5.2563E+07	4.9443E+06

E-3: Neutron Spectrum at a range of 170 meters (1980).

GROUP	PARTICLES/CM2-RAH	E * PHI (E)
1		
2		
3		
4		
5		
6		
7		
8		
9	2.8069E+04	2.8120E+05
10	4.1031E+04	4.1094E+05
11	6.0096E+04	6.0046E+05
12	1.6822E+05	1.1106E+06
13	5.4546E+05	2.1843E+06
14	1.9573E+05	3.8173E+06
15	5.2108E+05	3.5170E+06
16	1.2932E+06	4.2662E+06
17	1.8590E+06	7.1828E+06
18	3.0831E+05	8.8868E+06
19	2.0448E+06	8.7788E+06
20	4.1038E+06	8.2625E+06
21	6.4069E+06	1.0415E+07
22	1.0885E+07	8.7287E+06
23	2.8721E+06	8.1348E+06
24	5.8058E+06	7.7543E+06
25	5.4478E+06	7.2638E+06
26	8.6835E+05	6.9928E+06
27	5.0761E+06	6.7282E+06
28	6.9655E+06	6.2016E+06
29	5.5760E+06	5.6562E+06
30	4.0230E+06	5.2382E+06
31	8.2128E+06	4.6989E+06
32	5.1429E+06	4.1212E+06
33	3.7252E+06	3.7362E+06
34	4.2410E+06	3.3878E+06
35	3.0593E+06	3.0710E+06
36	2.8260E+06	2.8144E+06
37	1.8993E+07	1.7862E+06

E-4: Neutron Spectrum at a range of 179 meters (1981).

GROUP	PARTICLES/CM2-KWH	E * PHI (E)
1		
2		
3		
4		
5		
6		
7		
8		
9	1.8801E+06	1.8837E+06
10	3.2278E+06	3.2356E+06
11	4.9873E+06	4.9983E+06
12	1.2553E+07	8.2676E+06
13	4.0482E+06	1.6[illegible]E+06
14	1.3760E+07	2.6661E+06
15	3.8736E+06	2.6145E+06
16	9.5903E+05	3.1756E+06
17	1.3220E+06	5.7318E+06
18	2.5763E+05	7.9872E+06
19	1.7429E+06	7.4824E+06
20	3.3821E+06	6.7647E+06
21	5.1217E+06	8.2255E+06
22	8.7605E+06	7.0225E+06
23	2.3308E+06	6.6017E+06
24	4.7302E+06	6.3284E+06
25	4.4802E+06	5.9736E+06
26	7.1823E+05	5.7755E+06
27	4.2124E+06	5.5842E+06
28	5.8360E+06	5.1959E+06
29	4.7227E+06	4.7966E+06
30	3.4362E+06	4.4776E+06
31	7.1087E+06	4.2671E+06
32	4.5207E+06	3.6029E+06
33	3.3128E+06	3.0026E+06
34	3.8152E+06	3.1477E+06
35	2.7841E+06	2.7848E+06
36	2.5904E+06	2.5877E+06
37	2.0330E+07	1.8[illegible]E+06

E-5: Neutron Spectrum at a range of 260 meters (1981).

GROUP	PARTICLES/CM2-KWH	E * PHI (E)
1		
2		
3		
4		
5		
6		
7		
8		
9	5.7521E+03	5.7625E+04
10	8.3660E+03	8.3784E+04
11	1.1784E+04	1.1784E+05
12	3.3941E+04	2.2878E+05
13	1.1320E+05	4.5328E+05
14	3.9629E+04	6.8441E+05
15	9.1907E+04	6.2033E+05
16	2.2332E+05	7.4621E+05
17	3.3862E+05	1.4681E+06
18	6.9208E+04	2.3328E+06
19	4.7741E+05	2.0456E+06
20	8.3991E+05	1.8[illegible]E+06
21	1.2848E+06	2.0884E+06
22	2.2433E+06	1.7985E+06
23	6.0667E+05	1.7183E+06
24	1.2470E+06	1.6695E+06
25	1.1971E+06	1.5961E+06
26	1.9361E+05	1.5569E+06
27	1.1456E+06	1.5187E+06
28	1.6174E+06	1.4410E+06
29	1.3371E+06	1.3563E+06
30	9.9085E+05	1.2974E+06
31	2.1007E+06	1.2019E+06
32	1.3772E+06	1.1027E+06
33	1.0024E+06	1.0[illegible]E+06
34	1.2160E+06	9.7[illegible]E+05
35	8.0795E+05	8.1141E+05
36	8.6465E+05	8.6112E+05
37	6.7122E+06	6.3136E+05

E-6: Neutron spectrum at a range of 300 meters (1980).

GROUP	PARTICLES/CM2-KWH	E * PHI (E)
1		
2		
3		
4		
5		
6		
7		
8		
9	4.4744E+03	4.4820E+04
10	9.8975E+03	9.9063E+04
11	1.0588E+04	1.0588E+05
12	2.4396E+04	1.6301E+05
13	8.5272E+04	3.4143E+05
14	2.6734E+04	5.1788E+05
15	6.8448E+04	4.6048E+05
16	1.6702E+05	5.5359E+05
17	2.4268E+05	1.0512E+06
18	4.9432E+04	1.6344E+06
19	3.0281E+05	1.3000E+06
20	5.4726E+05	1.0946E+06
21	8.6756E+05	1.4102E+06
22	1.5216E+06	1.2199E+06
23	4.1123E+05	1.1647E+06
24	8.4488E+05	1.1284E+06
25	8.1055E+05	1.0808E+06
26	1.3105E+05	1.0539E+06
27	7.7515E+05	1.0276E+06
28	1.0935E+06	9.7361E+05
29	9.0322E+05	9.1622E+05
30	6.6866E+05	8.7156E+05
31	1.4166E+06	8.1046E+05
32	9.2757E+05	7.4335E+05
33	6.9472E+05	6.9677E+05
34	8.1702E+05	6.5214E+05
35	6.0983E+05	6.1216E+05
36	5.8028E+05	5.7751E+05
37	4.5038E+06	4.2365E+05

E-7: Neutron Spectrum at a range of 400 meters (1980).

GROUP	PARTICLES/CM2-KWH	E * PHI (E)
1		
2		
3		
4		
5		
6		
7		
8		
9	1.4693E+03	1.4719E+04
10	2.2202E+03	2.2236E+04
11	3.5397E+03	3.5366E+04
12	6.2231E+03	6.1626E+04
13	3.0226E+04	1.2103E+05
14	7.8676E+03	1.5244E+05
15	1.8794E+04	1.3359E+05
16	4.9823E+04	1.6514E+05
17	8.0627E+04	3.4957E+05
18	1.5185E+04	4.4602E+05
19	8.8265E+04	4.2186E+05
20	1.7599E+05	3.5201E+05
21	2.8648E+05	4.6565E+05
22	5.0864E+05	4.0859E+05
23	1.3825E+05	3.9440E+05
24	2.8823E+05	3.8496E+05
25	2.7834E+05	3.7247E+05
26	4.5433E+04	3.6534E+05
27	2.7033E+05	3.5837E+05
28	3.8623E+05	3.4387E+05
29	3.2381E+05	3.2827E+05
30	2.4251E+05	3.1582E+05
31	5.2239E+05	2.9887E+05
32	3.4909E+05	2.7976E+05
33	2.8547E+05	2.6626E+05
34	3.1722E+05	2.5341E+05
35	2.4029E+05	2.4116E+05
36	2.3172E+05	2.3077E+05
37	1.5787E+06	1.4859E+05

E-8: Neutron Spectrum at a range of 1080 meters (1980).

GROUP	PARTICLES/CM2-KWH	E * PHI (E)
1		
2		
3		
4		
5		
6		
7		
8		
9	7.1110E+00	7.1238E+01
10	4.6305E+00	4.6374E+01
11	1.1272E+01	1.1262E+02
12	2.9878E+01	1.9964E+02
13	1.1396E+02	4.9629E+02
14	3.6496E+01	7.0713E+02
15	7.8036E+01	5.2668E+02
16	1.3281E+02	4.4022E+02
17	2.6406E+02	1.1449E+03
18	5.8848E+01	1.7285E+03
19	3.7326E+02	1.6025E+03
20	6.4502E+02	1.2961E+03
21	1.0597E+03	1.7225E+03
22	1.8188E+03	1.5383E+03
23	5.3252E+02	1.5083E+03
24	1.1141E+03	1.4880E+03
25	1.0956E+03	1.4609E+03
26	1.7873E+02	1.4453E+03
27	1.0785E+03	1.4298E+03
28	1.5693E+03	1.3972E+03
29	1.3421E+03	1.3614E+03
30	1.0231E+03	1.3324E+03
31	2.2582E+03	1.2919E+03
32	1.5538E+03	1.2452E+03
33	1.2077E+03	1.2113E+03
34	1.4751E+03	1.1783E+03
35	1.1419E+03	1.1462E+03
36	1.1230E+03	1.1184E+03
37	4.7896E+03	4.5053E+02

E-9: Neutron Spectrum at a range of 1080 meters (1981).

GROUP	PARTICLES/CM2-KWH	E * PHI (E)
1		
2		
3		
4		
5		
6		
7		
8		
9	4.7008E-01	4.7093E+00
10	5.0602E+00	5.0678E+01
11	6.5719E+00	6.5664E+01
12	2.0673E+01	1.3813E+02
13	8.7478E+01	3.9031E+02
14	2.8737E+01	5.5681E+02
15	8.5116E+01	5.7446E+02
16	1.0108E+02	3.3502E+02
17	2.1682E+02	8.4006E+02
18	5.2748E+01	1.5493E+03
19	3.8754E+02	1.6637E+03
20	6.6286E+02	1.3258E+03
21	1.0026E+03	1.6297E+03
22	1.8179E+03	1.4574E+03
23	5.0520E+02	1.4309E+03
24	1.0578E+03	1.4129E+03
25	1.0416E+03	1.3888E+03
26	1.7098E+02	1.3748E+03
27	1.0268E+03	1.3612E+03
28	1.4863E+03	1.3322E+03
29	1.2819E+03	1.3004E+03
30	9.7863E+02	1.2745E+03
31	2.1644E+03	1.2383E+03
32	1.4929E+03	1.1964E+03
33	1.1625E+03	1.1660E+03
34	1.4225E+03	1.1363E+03
35	1.1032E+03	1.1074E+03
36	1.0867E+03	1.0823E+03
37	5.0679E+03	4.7671E+02

E-10: Neutron Spectrum at a range of 1080 meters (1982).

GROUP	PARTICLES/CM2-RWH	E * PHI (E)
1		
2		
3		
4		
5		
6		
7		
8		
9	3.7072E+00	3.7139E+01
10	7.7457E+00	7.7573E+01
11	9.9029E+00	9.8947E+01
12	2.7298E+01	1.8240E+02
13	1.0881E+02	4.3567E+02
14	3.5685E+01	6.8142E+02
15	8.3429E+01	5.6308E+02
16	1.3320E+02	4.4150E+02
17	2.6259E+02	1.1385E+03
18	6.2208E+01	1.6272E+03
19	4.2843E+02	1.8353E+03
20	7.0898E+02	1.4181E+03
21	1.0584E+03	1.7204E+03
22	1.8725E+03	1.5012E+03
23	5.1173E+02	1.4484E+03
24	1.0594E+03	1.4150E+03
25	1.0270E+03	1.3693E+03
26	1.6705E+02	1.3433E+03
27	9.9409E+02	1.3178E+03
28	1.4207E+03	1.2649E+03
29	1.1907E+03	1.2078E+03
30	8.9254E+02	1.1624E+03
31	1.9230E+03	1.1003E+03
32	1.2858E+03	1.0304E+03
33	9.7813E+02	9.8102E+02
34	1.1692E+03	9.3399E+02
35	8.8576E+02	8.8914E+02
36	8.5457E+02	8.5108E+02
37	4.2376E+03	3.9861E+02

APPENDIX F
GAMMA-RAY SPECTRA IN 21-GROUP FORMAT

APPENDIX F: GAMMA-RAY SPECTRA IN 21-GROUP FORMAT

In a manner identical to that previously described in Appendix E, the measured gamma-ray spectra of Appendix D are presented in a groupwise format consistent with the energy-group structure of the DLC-31 data library. In the case of gamma rays this includes twenty-one energy groups according to:

GROUP	UPPER ENERGY
1	14.0 MeV
2	10.0 "
3	8.0 "
4	7.0 "
5	6.0 "
6	5.0 "
7	4.0 "
8	3.0 "
9	2.5 "
10	2.0 "
11	1.5 "

GROUP	UPPER ENERGY
12	1.00 MeV
13	0.70 "
14	0.45 "
15	0.30 "
16	0.15 "
17	0.10 "
18	0.070 "
19	0.045 "
20	0.030 "
21	0.020 "
	0.010 "

The listed data are also identically normalized such that the applicable units are "photons per cm^2.kWh".

F-2: Gamma-ray spectrum at a range of 100m (1980).

GROUP	PARTICLES/CM2-KWH	E * PHI (E)
1		
2		
3	1.3832E+06	1.0358E+07
4	1.7851E+06	1.1580E+07
5	1.9269E+06	1.0569E+07
6	2.5196E+06	1.1291E+07
7	3.5208E+06	1.2238E+07
8	2.5203E+06	1.3823E+07
9	6.7988E+06	3.0468E+07
10	8.4791E+06	2.9474E+07
11	8.8178E+06	2.1747E+07
12	7.0882E+06	1.9873E+07
13	1.3577E+07	3.0729E+07
14	1.5546E+07	3.8342E+07
15		
16		
17		
18		
19		
20		
21		

F-3: Gamma-ray spectrum at a range of 170m (1980).

GROUP	PARTICLES/CM2-KWH	E * PHI (E)
1		
2		
3	4.5136E+05	3.3802E+06
4	6.2940E+05	4.0830E+06
5	6.8735E+05	3.7706E+06
6	1.0008E+06	4.4852E+06
7	1.1809E+06	4.1049E+06
8	8.0579E+05	4.4196E+06
9	2.3961E+06	1.0738E+07
10	2.9534E+06	1.0266E+07
11	2.7556E+06	6.7561E+06
12	2.2742E+06	6.3762E+06
13	4.5798E+06	1.0365E+07
14	5.4008E+06	1.3320E+07
15		
16		
17		
18		
19		
20		
21		

F-4: Gamma-ray spectrum at a range of 179m (1981).

GROUP	PARTICLES/CM2-KWH	E * PHI (E)
1		
2		
3	6.6118E+05	4.9515E+06
4	3.9375E+05	2.5543E+06
5	7.4028E+05	4.0603E+06
6	7.8916E+05	3.5365E+06
7	1.1365E+06	3.9507E+06
8	7.9557E+05	4.3630E+06
9	3.4801E+06	1.5596E+07
10	1.8416E+06	6.3994E+06
11	2.4761E+06	6.1069E+06
12	2.0748E+06	5.8170E+06
13	5.0301E+06	1.1385E+07
14	5.2242E+06	1.2884E+07
15		
16		
17		
18		
19		
20		
21		

F-5: Gamma-ray spectrum at a range of 260m (1981).

GROUP	PARTICLES/CM2-KWH	E * PHI (E)
1		
2		
3	1.8781E+05	1.4065E+06
4	1.3010E+05	8.4398E+05
5	2.7253E+05	1.4948E+06
6	2.4241E+05	1.0863E+06
7	3.7469E+05	1.3025E+06
8	2.8179E+05	1.5456E+06
9	1.2014E+06	5.3838E+06
10	6.0077E+05	2.0883E+06
11	7.3560E+05	1.8142E+06
12	6.5318E+05	1.8315E+06
13	1.4874E+06	3.3663E+06
14	1.6128E+06	3.9777E+06
15		
16		
17		
18		
19		
20		
21		

F-6: Gamma-ray spectrum at a range of 300m (1980).

GROUP	PARTICLES/CM2-KWH	E * PHI (E)
1		
2		
3	1.1843E+05	8.8687E+05
4	1.2575E+05	8.1575E+05
5	1.6050E+05	8.8032E+05
6	2.3133E+05	1.0367E+06
7	2.3297E+05	8.0982E+05
8	1.7258E+05	9.4657E+05
9	5.9208E+05	2.6534E+06
10	6.5891E+05	2.2904E+06
11	5.3392E+05	1.3168E+06
12	4.1390E+05	1.1604E+06
13	9.1723E+05	2.0760E+06
14	1.0918E+06	2.6927E+06
15		
16		
17		
18		
19		
20		
21		

F-7: Gamma-ray spectrum at a range of 400m (1980).

GROUP	PARTICLES/CM2-KWH	E * PHI (E)
1		
2		
3	4.8577E+04	3.6379E+05
4	4.7817E+04	3.1020E+05
5	7.0463E+04	3.8648E+05
6	8.7133E+04	3.9046E+05
7	9.2928E+04	3.2302E+05
8	6.5964E+04	3.6180E+05
9	2.3870E+05	1.0697E+06
10	1.9809E+05	6.8857E+05
11	1.0224E+05	4.4947E+05
12	1.4471E+05	4.0573E+05
13	3.4482E+05	7.8044E+05
14	3.9822E+05	9.8213E+05
15		
16		
17		
18		
19		
20		
21		

F-8: Gamma-ray spectrum at a range of 1080m (1980).

GROUP	PARTICLES/CM2-KWH	E * PHI (E)
1		
2		
3	1.9522E+02	1.4620E+03
4	3.9315E+02	2.5504E+03
5	7.6287E+02	4.1842E+03
6	9.4018E+02	4.2134E+03
7	8.4230E+02	2.9279E+03
8	4.9496E+02	2.7147E+03
9	1.0844E+03	4.6597E+03
10	1.1684E+03	4.0613E+03
11	1.3752E+03	3.3917E+03
12	1.1156E+03	3.1391E+03
13	2.3758E+03	5.3771E+03
14	2.7182E+03	6.7038E+03
15		
16		
17		
18		
19		
20		
21		

F-9: Gamma-ray spectrum at a range of 1080m (1981).

GROUP	PARTICLES/CM2-KWH	E * PHI (E)
1		
2		
3	1.1738E+02	8.7904E+02
4	3.4143E+02	2.2149E+03
5	9.6566E+02	5.2954E+03
6	7.2923E+02	3.2680E+03
7	8.6857E+02	3.0192E+03
8	5.0915E+02	2.7928E+03
9	1.1638E+03	5.2156E+03
10	1.1416E+03	3.9684E+03
11	1.4146E+03	3.4880E+03
12	1.2710E+03	3.5636E+03
13	2.6437E+03	5.8923E+03
14	2.6094E+03	6.9290E+03
15		
16		
17		
18		
19		
20		
21		

F-10: Gamma-ray spectrum at a range of 1080m (1982).

GROUP	PARTICLES/CM2-KWH	E * PHI (E)
1		
2		
3	3.0089E+02	2.2541E+03
4	3.0955E+02	2.0081E+03
5	1.0555E+03	5.7567E+03
6	8.4233E+02	3.7748E+03
7	8.5845E+02	2.9849E+03
8	5.4290E+02	2.9826E+03
9	1.1856E+03	5.3130E+03
10	1.1986E+03	4.1664E+03
11	1.5913E+03	3.9245E+03
12	1.4660E+03	4.1103E+03
13	2.8079E+03	6.3552E+03
14	2.9881E+03	7.3697E+03
15		
16		
17		
18		
19		
20		
21		

APPENDIX G
SUMMARY OF FREE-FIELD INTEGRAL MEASUREMENTS

APPENDIX G: SUMMARY OF FREE-FIELD INTEGRAL MEASUREMENTS

Included in this appendix are integral measurements obtained under free-field conditions at APRF since 1979 and subsequently reported by APRD, WWD and DREO as well as some more recent and as yet unreported measurements by APRD and DREO. Quantities tabulated include neutron, gamma-ray and total kermas as well as neutron fluence above 3 MeV energy. Data obtained using both integral detectors such as ion-chambers and proportional counters, and also data resulting from integration of measured particle spectra are included. Normalization in all cases has been made to kilowatt-hours and each quantity has been multiplied by $4\pi r^2$, where r is the source-to-detector distance. This converts the measured fluence to units of "neutrons per kWh" and kerma to "rad.cm^2 per kWh". In so doing that portion of the observed variation with distance due strictly to geometric attenuation is eliminated, leaving only the effects of scatter and absorption.

Thirty-two measurements of neutron fluence above 3 MeV are listed, as are thirty-six of neutron kerma, thirty-one of gamma-ray kerma, and thirty of total kerma. Neutron fluence above 3 MeV has been measured using both activation of sulfur tablets (APRD) and integration of NE-213 determinations of neutron spectra (APRD, WWD, DREO). Neutron kerma has been measured variously by six techniques, namely: difference between tissue-equivalent ion-chamber and Geiger-Müller counter doses (APRD), NE-213 spectroscopy above 550 keV with proton-recoil spectroscopy below 550 keV (APRD), pure NE-213 spectroscopy above 550 keV (WWD), microdosimetry using a Rossi-type tissue-equivalent proportional counter (DREO), NE-213 spectroscopy above 600 keV with boron-triflouride parametric analysis below 600 keV (DREO), and finally Bonner-ball few-group spectroscopy (APRD). Five of the above-mentioned techniques account for essentially all of the incident neutron kerma, however it should be noted that pure NE-213 determinations above 550 keV energy only account for approximately sixty-five percent of the total neutron kerma, the remainder falling below the lower detection threshold (in the particular neutron environment typical of APRD).

Gamma-ray kerma has been determined directly using Geiger-Müller counters (APRD), NE-213 spectroscopy (WWD, DREO) and microdosimetric techniques (DREO). Indirect measurement has also been made by subtracting Bonner-ball neutron kerma determinations from ion-chamber measurements of total kerma. NE-213 determinations are deficient in that gamma-rays of energy less than 450 keV (WWD) or 300 keV (DREO) are not detected, conseqently the estimation of gamma-kerma does not reflect that portion falling below these energies. The specific contribution to kerma below the NE-213 threshold is, however, small (of the order of 5%) and in comparison to the other methods experience has shown that NE-213 estimations tend in fact to be somewhat higher than GM counter measurements at short ranges, but equally lower at longer ranges. Based on the listed observations it is therefore concluded that the non-zero detection threshold of NE-213 does not bias the measurement of gamma-ray kerma unduly, or in excess of estimated experimental errors from other sources. It is indicated, however, that the spectral response of NE-213 and GM detectors are not entirely consistent. To date sufficient information from the other independent methods required to resolve this discrepancy is not available.

Total kerma (neutron plus gamma-ray) has been variously determined by employing four independent methods, namely: tissue-equivalent ion chamber (APRD), microdosimetric tissue-equivalent proportional chamber (DREO), combination of neutron and gamma kermas measured using NE-213 and BF_3 detectors (DREO), and addition of Bonner-ball neutron and GM gamma-ray determinations (APRD). Consistency between these methods is excellent at all ranges - surprisingly so in consideration that all four systems differ in design, calibration technique, and analytical methods. No significantly consistent variations are apparent in the measured data.

Averaged integral quantities as functions of range are also listed (Table G-2) on the last page of this appendix. For each range averages of all experimental measurements of each of the four integral quantities mentioned earlier are shown, with two exceptions. Measurements made at ranges of 179m and 260m are excluded as the reactor was physically located inside its silo at the time. Although the aluminum silo represents a minimal perturbation, in the interests of consistency only data obtained with the reactor outside have been included. Also excluded from contribution to these averages are measurements of neutron kerma obtained with pure NE-213 systems, due to the previously-noted loss of information below 550 KeV.

Within parentheses after each listed average is shown the standard deviation (sample) of the measurements with respect to the calculated mean value, expressed as a percentage of said mean. Thus, these deviations yield an indiction of the self-consistency of the measured data, at each range and for each quantity. Generally, these deviations indicate that there is very good consistency within the measurements, particularly so in light of the extended period of experimentation (five years), differences in technique, and inescapable variations in weather conditions and soil moisture content. The best consistency is evident in determination of total kerma (3 to 6%), other quantities being somewhat less consistently-measured (about 5 to 10%).

TABLE G-1

INTEGRAL QUANTITIES DETERMINED EXPERIMENTALLY AT APRF

NOTES:

1) 'YEAR' signifies year data reported, or obtained if not yet reported.

2) 'GROUP': APRD - ARMY PULSE RADIATION DIVISION (US)
WWD - WEHRWISSENSCHAFTLICHE DIENSTSTELLE DER BUNDESWEHR FUER ABC-SCHUTZ (FRG)
DREO - DEFENCE RESEARCH ESTABLISHMENT OTTAWA (CA)

3) 'TECHNIQUE': SULFUR - NEUTRON ACTIVATION OF SULFUR TABLETS
NE-213 - ORGANIC SCINTILLATOR SPECTROSCOPY
TE - TISSUE-EQUIVALENT ION CHAMBER
GM - GEIGER-MUELLER COUNTER
TE-GM - DIFFERENCE BETWEEN TE AND GM DATA
MICRODOSE - MICRODOSIMETRY USING 0.5" ROSSI COUNTER
BF_3 - BORON-TRIFLOURIDE COUNTER
PR - PROTON-RECOIL GAS COUNTER SPECTROSCOPY
BB - BONNER-BALL NEUTRON SPECTROSCOPY

4) 'QUANTITY': 3-MEV FLUX - $4\pi r^2$ * NEUTRON FLUX > 3 MeV (n/kWh)
NEUTRON KERMA - $4\pi r^2$ * Kn (rad.cm^2/kWh)
GAMMA KERMA - $4\pi r^2$ * Kg (rad.cm^2/kWh)
TOTAL KERMA - $4\pi r^2$ * (Kn + Kg) (rad.cm^2/kWh)

5) 'VALUE': 1.73 + 16 = 1.73×10^{16}, etc

6) 'ERROR': Percentage standard error of measurement, if quoted.

RANGE: 1 METER

YEAR	GROUP	TECHNIQUE	QUANTITY	VALUE	ERROR	NOTES
1976	APRD	SULFUR	3-MEV FLUX	1.73+16	5%	Horiz
1982	APRD	SULFUR	3-MEV FLUX	1.49+16	10%	4π

RANGE: 10 METERS

YEAR	GROUP	TECHNIQUE	QUANTITY	VALUE	ERROR	NOTES
1979	APRD	SULFUR	3-MEV FLUX	2.20+16		
1979	WWD	NE-213	3-MEV FLUX	1.88+16		

YEAR	GROUP	TECHNIQUE	QUANTITY	VALUE	ERROR	NOTES
1979	APRD	TE-GM	NEUTRON KERMA	4.26+8		
1979	APRD	NE-213+PR	NEUTRON KERMA	4.26+8		
1979	WWD	NE-213	NEUTRON KERMA	3.10+8		> 550 KEV
1980	DREO	MICRODOSE	NEUTRON KERMA	4.32+8		
1979	APRD	GM	GAMMA KERMA	3.86+7		
1979	WWD	NE-213	GAMMA KERMA	4.34+7		> 450 KEV
1980	DREO	MICRODOSE	GAMMA KERMA	3.90+7		
1979	APRD	TE	TOTAL KERMA	4.50+8		50 c.c.
1979	APRD	TE	TOTAL KERMA	4.76+8		4000 c.c.
1980	DREO	MICRODOSE	TOTAL KERMA	4.70+8		

RANGE: 15 METERS

YEAR	GROUP	TECHNIQUE	QUANTITY	VALUE	ERROR	NOTES
1980	DREO	NE-213	3-MEV FLUX	2.23+16	3%	
1980	DREO	NE-213+BF_3	NEUTRON KERMA	4.16+8	2%	

RANGE: 50 METERS

YEAR	GROUP	TECHNIQUE	QUANTITY	VALUE	ERROR	NOTES
1979	APRD	SULFUR	3-MEV FLUX	1.79+17		
1979	APRD	TE	TOTAL KERMA	4.99+8		

RANGE: 100 METERS

YEAR	GROUP	TECHNIQUE	QUANTITY	VALUE	ERROR	NOTES
1979	APRD	SULFUR	3-MEV FLUX	1.49+16	7%	
1979	APRD	NE-213	3-MEV FLUX	1.50+16		
1979	WWD	NE-213	3-MEV FLUX	1.32+16		
1980	APRD	SULFUR	3-MEV FLUX	1.34+16		1"
1980	APRD	SULFUR	3-MEV FLUX	1.54+16		2"
1980	DREO	NE-213	3-MEV FLUX	1.40+16	3%	
1979	APRD	TE-GM	NEUTRON KERMA	3.60+8		
1979	APRD	NE-213+PR	NEUTRON KERMA	3.38+8		
1979	WWD	NE-213	NEUTRON KERMA	2.77+8		> 550 KEV
1980	DREO	NE-213+BF_3	NEUTRON KERMA	3.21+8	2%	
1979	APRD	GM	GAMMA KERMA	5.20+7		
1979	WWD	NE-213	GAMMA KERMA	6.26+7		> 450 KEV
1980	DREO	NE-213	GAMMA KERMA	6.18+7	3%	> 300 KEV

YEAR	GROUP	TECHNIQUE	QUANTITY	VALUE	ERROR	NOTES
1980	APRD	TE	TOTAL KERMA	4.12+8		
1980	DREO	NE-213+BF_3	TOTAL KERMA	3.83+8	2%	

RANGE: 170 METERS

YEAR	GROUP	TECHNIQUE	QUANTITY	VALUE	ERROR	NOTES
1979	APRD	SULFUR	3-MEV FLUX	1.17+16	11%	
1979	APRD	NE-213	3-MEV FLUX	1.25+16		
1979	WWD	NE-213	3-MEV FLUX	9.85+16		
1980	APRD	SULFUR	3-MEV FLUX	1.08+16		1"
1980	APRD	SULFUR	3-MEV FLUX	1.11+16		2"
1980	DREO	NE-213	3-MEV FLUX	1.04+16	3%	
1979	APRD	TE-GM	NEUTRON KERMA	2.57+8		
1979	APRD	TE-GM	NEUTRON KERMA	2.78+8		
1979	APRD	NE-213+PR	NEUTRON KERMA	3.18+8		
1979	WWD	NE-213	NEUTRON KERMA	2.07+8		> 550 KEV
1980	DREO	NE-213+BF_3	NEUTRON KERMA	2.55+8	2%	
1980	DREO	MICRODOSE	NEUTRON KERMA	2.64+8		
1980	APRD	TE-GM	NEUTRON KERMA	2.45+8		
1981	APRD	BONNER BELL	NEUTRON KERMA	2.42+8		
1982	APRD	TE-GM	NEUTRON KERMA	2.51+8		
1979	APRD	GM	GAMMA KERMA	5.81+7		
1979	APRD	GM	GAMMA KERMA	7.02+7		
1979	WWD	GM	GAMMA KERMA	5.44+7		
1979	WWD	NE-213	GAMMA KERMA	6.23+7		> 450 KEV
1980	DREO	NE-213	GAMMA KERMA	6.12+7	3%	> 300 KEV
1980	DREO	MICRODOSE	GAMMA KERMA	5.74+7		
1980	APRD	GM	GAMMA KERMA	7.48+7		
1982	APRD	GM	GAMMA KERMA	6.54+7	11%	
1982	APRD	TE-BB	GAMMA KERMA	7.40+7	9%	
1979	APRD	TE	TOTAL KERMA	3.15+8		
1979	APRD	TE	TOTAL KERMA	3.48+8		
1980	DREO	NE-213+BF_3	TOTAL KERMA	3.16+8	2%	
1980	DREO	MICRODOSE	TOTAL KERMA	3.21+8		
1980	APRD	TE	TOTAL KERMA	3.20+8		
1982	APRD	TE	TOTAL KERMA	3.16+8		

RANGE: 179 METERS (REACTOR INSIDE SILO)

YEAR	GROUP	TECHNIQUE	QUANTITY	VALUE	ERROR	NOTES
1981	DREO	NE-213	3-MEV FLUX	8.60+15	4%	
1981	DREO	NE-213+BF_3	NEUTRON KERMA	2.26+8	2%	
1981	DREO	NE-213	GAMMA KERMA	6.78+7	3%	> 300 KEV

YEAR	GROUP	TECHNIQUE	QUANTITY	VALUE	ERROR	NOTES
1981	DREO	NE-213+BF_3	TOTAL KERMA	2.94+8	2%	

RANGE: 250 METERS

YEAR	GROUP	TECHNIQUE	QUANTITY	VALUE	ERROR	NOTES
1978	APRD	TE	TOTAL KERMA	2.12+8		

RANGE: 260 METERS (REACTOR INSIDE [illegible]LO)

YEAR	GROUP	TECHNIQUE	QUANTITY	VALUE	ERROR	NOTES
1981	DREO	NE-213	3-MEV FLUX	4.56+15	2%	
1981	DREO	NE-213+BF_3	NEUTRON KERMA	1.24+8	2%	
1981	DREO	NE-213	GAMMA KERMA	4.69+7	3%	> 300 KEV
1981	DREO	NE-213+BF_3	TOTAL KERMA	1.71+8	4%	

RANGE: 300 METERS

YEAR	GROUP	TECHNIQUE	QUANTITY	VALUE	ERROR	NOTES
1979	APRD	SULFUR	3-MEV FLUX	6.14+15	20%	
1979	APRD	NE-213	3-MEV FLUX	5.49+15		
1979	WMD	NE-213	3-MEV FLUX	4.14+15		
1980	APRD	SULFUR	3-MEV FLUX	5.65+15		1"
1980	APRD	SULFUR	3-MEV FLUX	4.68+15		2"
1980	DREO	NE-213	3-MEV FLUX	4.49+15	4%	
1979	APRD	TE-GM	NEUTRON KERMA	1.27+8		
1979	WMD	NE-213	NEUTRON KERMA	9.13+7		
1980	DREO	NE-213+BF_3	NEUTRON KERMA	1.12+8	2%	> 550 KEV
1979	APRD	GM	GAMMA KERMA	3.76+7		
1979	WMD	NE-213	GAMMA KERMA	3.87+7		> 450 KEV
1980	DREO	NE-213	GAMMA KERMA	4.15+7	3%	> 300 KEV
1979	APRD	TE	TOTAL KERMA	1.64+8		
1980	DREO	NE-213+BF_3	TOTAL KERMA	1.53+8	2%	

RANGE: 350 METERS

YEAR	GROUP	TECHNIQUE	QUANTITY	VALUE	ERROR	NOTES
1978	APRD	TE	TOTAL KERMA	1.23+8		

RANGE: 400 METERS

YEAR	GROUP	TECHNIQUE	QUANTITY	VALUE	ERROR	NOTES
1980	APRD	SULFUR	3-MEV FLUX	2.57+15		
1980	DREO	NE-213	3-MEV FLUX	2.55+15	3%	
1980	APRD	TE-GM	NEUTRON KERMA	6.79+7		
1980	DREO	NE-213+BF_3	NEUTRON KERMA	6.56+7	2%	
1980	APRD	GM	GAMMA KERMA	2.68+7		
1980	DREO	NE-213	GAMMA KERMA	2.82+7	3%	> 300 KEV
1980	APRD	TE	TOTAL KERMA	9.47+7		
1980	DREO	NE-213+BF_3	TOTAL KERMA	9.38+7	2%	

RANGE: 434 METERS

YEAR	GROUP	TECHNIQUE	QUANTITY	VALUE	ERROR	NOTES
1980	APRD	SULFUR	3-MEV FLUX	2.16+15		2"

RANGE: 1080 METERS

YEAR	GROUP	TECHNIQUE	QUANTITY	VALUE	ERROR	NOTES
1980	DREO	NE-213	3-MEV FLUX	6.19+13	5%	
1981	DREO	NE-213	3-MEV FLUX	5.19+13	5%	
1982	DREO	NE-213	3-MEV FLUX	6.07+13	6%	HIGH T&H
1980	DREO	NE-213+BF_3	NEUTRON KERMA	1.74+6	3%	
1980	APRD	TE-GM	NEUTRON KERMA	1.55+6		WITH DREO
1980	APRD	TE-GM	NEUTRON KERMA	1.71+6		
1981	DREO	NE-213+BF_3	NEUTRON KERMA	1.64+6	3%	
1981	APRD	TE-GM	NEUTRON KERMA	1.44+6	32%	WITH DREO
1981	APRD	BONNER BALL	NEUTRON KERMA	1.60+6	10%	WITH DREO
1982	DREO	NE-213+BF_3	NEUTRON KERMA	1.76+6	3%	HIGH T&H
1982	APRD	BONNER BALL	NEUTRON KERMA	1.74+6		WITH DREO
1982	APRD	BONNER BALL	NEUTRON KERMA	1.97+6		HIGH T&H
1980	DREO	NE-213	GAMMA KERMA	1.57+6	10%	> 300 KEV
1980	APRD	GM	GAMMA KERMA	1.89+6		WITH DREO
1980	APRD	GM	GAMMA KERMA	2.05+6		
1981	DREO	NE-213	GAMMA KERMA	1.63+6	10%	> 300 KEV
1981	APRD	GM	GAMMA KERMA	1.88+6	20%	WITH DREO
1982	DREO	NE-213	GAMMA KERMA	1.77+6	6%	HIGH T&H
1982	APRD	TE-BB	GAMMA KERMA	1.78+6	14%	

YEAR	GROUP	TECHNIQUE	QUANTITY	VALUE	ERROR	NOTES
1980	DREO	NE-213+BF_3	TOTAL KERMA	3.32+6	5%	
1980	APRD	TE	TOTAL KERMA	3.44+6		WITH DREO
1980	APRD	TE	TOTAL KERMA	3.76+6		
1980	APRD	TE	TOTAL KERMA	3.31+6		
1981	DREO	NE-213+BF_3	TOTAL KERMA	3.27+6	5%	
1981	APRD	TE	TOTAL KERMA	3.32+6	8%	
1982	DREO	NE-213+BF_3	TOTAL KERMA	3.53+6	4%	HIGH T&H
1982	APRD	TE	TOTAL KERMA	3.45+6	9%	

RANGE: 1618 METERS

YEAR	GROUP	TECHNIQUE	QUANTITY	VALUE	ERROR	NOTES
1982	APRD	BONNER BALL	NEUTRON KERMA	1.12+5	20%	HIGH T&H
1982	APRD	TE-GM	NEUTRON KERMA	1.45+5	33%	"
1982	APRD	GM	GAMMA KERMA	2.53+5	12%	"
1982	APRD	TE-BB	GAMMA KERMA	2.86+5	16%	"
1982	APRD	TE	TOTAL KERMA	3.98+5	10%	"
1982	APRD	BB+GM	TOTAL KERMA	3.65+5	10%	"

TABLE G-2

AVERAGE INTEGRAL DATA OBTAINED EXPERIMENTALLY

RANGE (meters)	3-MEV FLUX (n/kWh)	NEUTRON KERMA (rad.cm^2/kWh)	GAMMA KERMA (rad.cm^2/kWh)	TOTAL KERMA (rad.cm^2/kWh)
1	1.49+16 (4π) 1.73+16 (Horizontal)			
10	2.04+16 (11%)	4.28+8 (1%)	4.03+7 (7%)	4.65+8 (3%)
15	2.23+16	4.16+8		
50	1.79+17			
100	1.43+16 (6%)	3.40+8 (6%)	5.88+7 (10%)	3.98+8 (5%)
170	1.11+16 (9%)	2.64+8 (9%)	6.42+7 (12%)	3.23+8 (4%)
250				2.12+8
300	5.10+15 (15%)	1.20+8 (9%)	3.93+7 (5%)	1.59+8 (5%)
350				1.23+8
400	2.56+15 (1%)	6.68+7 (2%)	2.75+7 (4%)	9.43+7 (1%)
434	2.16+15			
1080	5.82+13 (9%)	1.68+6 (9%)	1.80+6 (9%)	3.43+6 (5%)
1618		1.29+5 (18%)	2.70+5 (9%)	3.82+5 (6%)

NOTES: 1) Only data obtained with the reactor operating outdoors have been included.

2) Pure NE-213 determinations of neutron kerma above 550 KeV have been excluded.

3) Percentages in brackets signify observed standard deviations of all the measured data, relative to the quoted mean value. Where none listed, the mean value quoted results from a single measurement.

APPENDIX H
THEORETICALLY-CALCULATED INTEGRAL QUANTITIES

APPENDIX H: THEORETICALLY-CALCULATED INTEGRAL QUANTITIES

Theoretically-calculated values of neutron fluence above 3 MeV and neutron, gamma-ray and total kerma available as of the date of this report include those determined at ORNL (1978), DREO (1980), SAI (1982) and LLNL (1982). Theoretical values for these quantities are listed in Table H-1 at the five ranges at which the majority of measurements were performed, namely 100, 170, 300, 400 and 1080 meters. Where quantities have been calculated at points differing in range to the experiments, these have been interpolated in a semi-logarithmic manner as a correction to the calculations. Also shown for comparison are the mean values of those measured quantities previously listed in Table G-2.

In Table H-2 the ratios of calculated value to mean experimental measurement are also shown for each range and quantity. To assist in assessing the significance of individual calculated-to-experimental differences, the relative standard deviations of the measurements from Table G-2 are also shown for each range and quantity.

Mean values of the ratios, averaged in an unweighted manner over the five ground ranges listed, are also shown for each quantity and calculation. A mean ratio departing significantly from the value '1' would thus indicate that a particular calculation systematically over- or under-predicts corresponding experimental results. The level of significance may be judged by comparing the calculated root-mean-square deviation from the value '1' (shown also immediately below each mean ratio) with comparable r.m.s. deviations observed within the measurements themselves, also listed. Thus, a comparison is made between the degree of "scatter" of the calculations about the mean experimental values and the degree of "scatter" exhibited by the experiments themselves about their own mean values.

For example, earlier ORNL and DREO calculations appear to under-predict neutron fluence above 3 MeV by a systematic thirty percent. The calculated r.m.s. deviations in the range of 0.35 are in excess by more than a factor of three than the observed r.m.s. deviations in the experimental data, thus it must be concluded that the above-noted under-prediction is of significant magnitude. In contrast, the calculated values of neutron, gamma-ray, and total kerma are in much better agreement with the experiments, especially so in the case of SAI and LLNL results. The earlier calculations of ORNL and DREO appear to be somewhat deficient in the determination of gamma-ray kerma and consequently also of total kerma to the extent that gamma-ray kerma contributes to this quantity. The calculations by SAI exhibit somewhat lower r.m.s. deviations than do those of LLNL, and also better calculated-to-experimental mean ratios. The variations attributed to the SAI results are consistent with the observed variations in the experimental values themselves, thus indicating that there is no statistically-significant difference between SAI predictions and experimental dosimetry.

TABLE H-1

CALCULATED INTEGRAL DATA INTERPOLATED AT EXPERIMENTAL POINTS

NOTES: 1) Calculated values are all normalized to 1.10+17 source neutrons per kilowatt-hour.

2) Neutron quantities interpolated as exp(-r/L) using L = 186 meters.

3) Gamma-ray quantities interpolated as exp(-r/L) using L = 258 meters.

>3-MeV NEUTRON FLUX (n/kWh)

RANGE	ORNL (1978)	DREO (1980)	SAI (1982)	LLNL (1982)	<EXPT>
100 m	1.01+16	9.11+15	1.28+16	1.40+16	1.43+16
170 m	6.67+15	6.38+15	8.47+15	9.39+15	1.11+16
300 m	3.30+15	2.98+15	3.74+15	4.29+15	5.10+15
400 m	1.91+15	1.74+15	2.32+15	2.39+15	2.56+15
1080 m		5.37+13	6.56+13	5.26+13	5.82+13

NEUTRON KERMA (rad.cm^2/kWh)

RANGE	ORNL (1978)	DREO (1980)	SAI (1982)	LLNL (1982)	<EXPT>
100 m	3.00+8	2.36+8	3.25+8	3.72+8	3.40+8
170 m	2.20+8	2.30+8	2.50+8	2.94+8	2.64+8
300 m	1.19+8	1.20+8	1.32+8	1.56+8	1.20+8
400 m	6.87+7	6.50+7	7.95+7	9.18+7	6.68+7
1080 m		2.09+6	1.71+6	1.85+6	1.68+6

GAMMA-RAY KERMA (rad.cm^2/kWh)

RANGE	ORNL (1978)	DREO (1980)	SAI (1982)	LLNL (1982)	<EXPT>
100 m	6.38+7	4.84+7	6.35+7	6.05+7	5.88+7
170 m	5.47+7	4.39+7	5.74+7	5.47+7	6.42+7
300 m	2.66+7	2.74+7	3.84+7	3.72+7	3.93+7
400 m	2.54+7	1.87+7	2.65+7	2.54+7	2.75+7
1080 m		1.62+6	1.65+6	1.39+6	1.80+6

TOTAL KERMA (rad.cm^2/kWh)

RANGE	ORNL (1978)	DREO (1980)	SAI (1982)	LLNL (1982)	<EXPT>
100 m	3.64+8	2.84+8	3.89+8	4.32+8	3.98+8
170 m	2.75+8	2.74+8	3.07+8	3.48+8	3.23+8
300 m	1.46+8	1.47+8	1.70+8	1.93+8	1.59+8
400 m	9.41+7	8.37+7	1.06+8	1.17+8	9.43+7
1080 m		3.71+6	3.36+6	3.25+6	3.43+6

TABLE H-2

RATIOS OF CALCULATED TO AVERAGE EXPERIMENTAL DATA

>3-MeV NEUTRON FLUX

RANGE	ORNL (1978)	DREO (1980)	SAI (1982)	LLNL (1982)	EXP. DEV.
100 m	0.71	0.64	0.90	0.98	6 %
170 m	0.60	0.57	0.76	0.85	9 %
300 m	0.65	0.58	0.73	0.84	15 %
400 m	0.75	0.68	0.91	0.93	1 %
1080 m		0.92	1.13	0.90	9 %
MEAN	0.68	0.68	0.89	0.90	-
RMS DEV	0.33	0.35	0.18	0.11	0.09

NEUTRON KERMA

RANGE	ORNL (1978)	DREO (1980)	SAI (1982)	LLNL (1982)	EXP. DEV.
100 m	0.88	0.69	0.96	1.09	6 %
170 m	0.83	0.87	0.95	1.11	9 %
300 m	0.99	1.00	1.10	1.30	9 %
400 m	1.03	0.97	1.19	1.37	2 %
1080 m		1.24	1.02	1.10	9 %
MEAN	0.93	0.95	1.04	1.19	-
RMS DEV	0.09	0.19	0.10	0.23	0.08

GAMMA-RAY KERMA

RANGE	ORNL (1978)	DREO (1980)	SAI (1982)	LLNL (1982)	EXP. DEV.
100 M	1.09	0.82	1.09	1.03	10 %
170 M	0.85	0.68	0.89	0.85	12 %
300 M	0.68	0.70	0.98	0.95	5 %
400 M	0.92	0.68	0.96	0.92	4 %
1080 M		0.90	0.92	0.77	9 %
MEAN	0.89	0.76	0.97	0.90	-
RMS DEV	0.19	0.26	0.07	0.13	0.08

TOTAL KERMA

RANGE	ORNL (1978)	DREO (1980)	SAI (1982)	LLNL (1982)	EXP. DEV.
100 m	0.91	0.71	0.98	1.09	5 %
170 m	0.85	0.85	0.95	1.08	4 %
300 m	0.92	0.92	1.07	1.21	5 %
400 m	0.89	1.00	1.12	1.24	1 %
1080 m		1.08	0.98	0.95	5 %
MEAN	0.89	0.91	1.02	1.11	-
RMS DEV	0.11	0.15	0.07	0.15	0.04

APPENDIX I
APRF SOIL COMPOSITION

APPENDIX I: APRF SOIL COMPOSITION

During July 1982, soil samples were obtained at seven different distances from the APRF core, at a depth of ten centimeters below grade. This particular depth was chosen as it corresponds roughly to a mean-free-path for fast neutrons in earth.

Density and moisture content determinations were made at DREO following which elemental analyses were performed by outside laboratories, the results being listed in Table I-1. Analysis for carbon, hydrogen, nitrogen, oxygen and silicon were performed by Beak Analytical Services of Toronto, the remaining elemental concentrations being determined by Bondar-Clegg and Company of Ottawa. In addition to individual concentrations for elements within each soil sample, also listed are mean concentrations of each element averaged over all seven soil samples.

Although the elements chosen for analysis comprise 98.9% by weight of the earth's crust, it is surprising that the average concentrations of these elements total only 74.9%. Two explanations for this discrepancy are possible - either the "missing" elements comprise the remaining 25.1 wt-%; or one or more of the elemental concentrations has been seriously underestimated. Of these two alternatives the latter is considered the more likely.

In particular the concentrations listed for silicon (mean of 14.7 wt-%) appear low for two reasons. According to the 49th Edition of the Chemical Rubber Company's "Handbook of Chemistry and Physics", 27.7 wt-% of the earth's crust is composed of silicon and that average igneous rocks, shales and sediments contain approximately 58 wt-% silicon dioxide (of which 27 wt-% would be due to silicon). It would therefore seem reasonable to increase the average silicon determination by 13 wt-%. Secondly, the analysed oxygen soil content of 36.3 wt-% is in excess by 11.6 wt-% of that required to completely oxidize all of the other constituents. If this "extra" oxygen were chemically bound to silicon the additional silicon required would amount to 13.3 wt-%, which is also consistent with the first consideration cited above.

Assuming that the listed concentrations of silicon were therefore increased by 13 wt-% to 27.7 wt-%, the total concentration of the nineteen elements would become 87.9 wt-%, for a shortfall of only 12.1 wt-%. Since no other inconsistency is immediately obvious, it would thus seem unavoidable to further increase all the analyses listed by a factor of 1.14, to make up for this shortfall.

Following this procedure, absolute elemental concentrations are listed in Table I-2 in units of atoms per barn-cm (or atoms per $cm^2 \times 10^{-24}$). For comparison earlier results quoted by APRD and WWD are also shown. Note that DREO estimates of hydrogen and oxygen concentrations are generally lower than either the APRD or WWD results. This arises as a consequence of the season during which soil sampling was performed. Both APRD and WWD samples were obtained in the spring (March 1978) and would be expected to be of somewhat higher moisture content than the DREO sampling during the summer (July 1982).

Also listed in Table I-2 are total densities calculated on the basis of individually-listed elemental concentrations in comparison to direct measurements by physical methods. These compare identically in the case of DREO results since normalization to 100% of the measured density was forced, as previously discussed. Conversely an overevaluation is apparent in the APRD results, indicating that one or more of the elemental analyses listed was excessive. It is not known whether WWD results were renormalized to a 100 wt-% total or not, given the good agreement between calculated and measured density.

TABLE I-1

RESULTS OF ELEMENTAL ANALYSIS OF DREO SOIL SAMPLING AT APRD

Sample Number:	1	2	3	4	5	6	7	MEAN
Range (Meters):	20	100	200	300	400	600	1080	-
Density (g/cc):	1.77	1.71	1.76	1.81	1.73	1.77	1.70	1.75
Moisture (wt-%):	14.7	12.6	15.9	16.9	20.4	15.7	14.3	15.8
ELEMENT	CONCENTRATION (wt-%)							
Hydrogen (moisture)	1.64	1.41	1.78	1.89	2.28	1.76	1.60	1.77
Hydrogen (soil)	0.28	0.31	0.21	0.27	0.19	0.30	0.35	0.27
Oxygen (moisture)	13.1	11.2	14.1	15.0	18.1	13.9	12.7	14.0
Oxygen (soil)	37.1	37.2	36.2	36.1	34.1	36.2	37.0	36.3
Carbon	0.77	0.45	0.43	0.46	0.82	0.16	0.23	0.47
Silicon	12.8	13.9	16.7	13.7	14.9	15.5	15.6	14.7
Nitrogen	.077	.052	.050	.075	.120	.051	.056	.069
Aluminium	3.79	3.95	3.23	4.09	2.42	4.40	5.04	3.85
Iron	1.77	2.41	1.35	1.93	1.21	1.79	2.57	1.86
Sodium	0.38	0.32	0.32	0.31	0.31	0.37	0.35	0.34
Magnesium	0.24	0.26	0.20	0.22	0.15	0.27	0.29	0.23
Potassium	0.89	0.84	0.81	0.80	0.60	0.88	0.96	0.83
Calcium	0.15	0.14	0.10	0.12	.096	.084	.069	.108
Sulphur	.016	.0096	.013	.016	.011	.011	.0077	.012
Chlorine	.026	.016	.0076	.0058	.0048	.023	.011	.013
Manganese	.044	.019	.035	.130	.032	.012	.012	.041
Copper	.0077	.0018	.0017	.0017	.0024	.0034	.0034	.0032
Boron	.00005	.00005	.00005	.00005	.00004	.00005	.00005	.00005
Nickel	.0017	.0018	.0017	.0017	.0016	.0017	.0017	.0017
Cobalt	.0017	.0018	.0017	.0017	.0016	.0017	.0017	.0017
Tin	.0009	.0009	.0008	.0008	.0008	.0008	.0017	.0009
TOTAL (wt-%):	73.1	72.5	79.4	75.2	75.3	75.7	76.8	74.9

TABLE I-2

ABSOLUTE ELEMENTAL CONCENTRATIONS OF APRD SOIL (atoms/barn-cm)

ELEMENT	APRD		WWD		DREO
	"DRY"	"WET"	#1	#2	MEAN
Hydrogen	3.0-2	5.4-2	4.2-2	3.9-2	2.4-2
Oxygen	5.3-2	6.5-2	3.6-2	4.3-2	3.8-2
Carbon			1.6-3	1.5-3	4.7-4
Silicon	1.9-2	1.9-2	7.2-3	1.1-2	1.2-2
Nitrogen					5.9-5
Aluminum	1.3-3		2.5-4	3.5-4	1.7-3
Iron	3.5-4		8.4-5	1.1-4	4.0-4
Sodium	2.6-4		1.5-4	2.0-4	1.8-4
Magnesium	6.0-5		2.5-4	3.0-4	1.1-4
Potassium	2.5-4		4.5-4	6.0-4	2.6-4
Calcium	3.0-7		1.6-3	2.0-3	3.2-5
Sulphur	9.0-5				4.5-6
Chlorine	1.0-6				4.4-6
Manganese	1.0-4				9.0-6
Copper	1.6-6				6.1-7
Boron	1.0-6				5.6-8
Nickel	2.0-7				3.5-7
Cobalt	2.0-7				3.5-7
Tin					9.1-8
Phosphorus	1.0-8				
Calculated density:	2.48	2.84	1.57	1.97	1.76
Measured density:	1.9	2.1*	1.5	1.9	1.75

* Scaled from "dry" soil density since "wet" soil had an 11.5% greater APRD-measured water content.

APPENDIX J
NEUTRON AND GAMMA-RAY SPECTRA FROM Cf^{252}

APPENDIX J: NEUTRON AND GAMMA-RAY SPECTRA FROM Cf^{252}

Neutrons emitted by Cf^{252} sources are often utilized to verify the correct operation of fast-neutron spectrometers since the particular spectrum is known to be approximately Maxwellian in shape [1], at an effective temperature of 1.41 MeV. The DREO NE-213 scintillator has for this reason been exposed to the APRD Cf^{252} source on two occasions, once during 1980 [2] and more recently on 26 Oct 1981. The 1981 measurement was performed inside the APRD silo at a height of 125 cm above the borated-concrete floor, and at a source-to-detector separation of 100 cm (± 1 cm). The total observation time was two hours, during which the shut-down reactor core was kept confined within its shielded enclosure beneath the floor.

The unfolded neutron spectrum so determined is shown in Figure J-1, plotted in such a manner as to reproduce a Maxwellian-like spectrum as a straight line, namely by dividing the energy-dependent flux by the square-root of the energy. The line plotted in comparison to the experimental points has been fitted to the measured data such that the neutron flux may be represented by:

$$\phi(E) = 143 \sqrt{E}\, e^{-E/1.427}$$

where the units of ϕ are neutrons per cm^2.MeV.sec if E is measured in MeV.

The effective temperature of 1.427 MeV is consistent with previous observations, and integration of the parametric Maxwellian from zero to infinity yields a total fluence at the point of observation of 215 neutrons per cm^2.sec. Multiplying by $4\pi r^2$ thus indicates an effective neutron emission rate of 2.70×10^7 neutrons per second. This source had previously been calibrated by the manufacturer (Monsanto) as emitting 4.44×10^7 (±3%) neutrons per second on 11 Jan 1980. Correcting for source decay during the intervening period using a half-life of 2.65 years, the expected yield on the date of measurement was 2.78×10^7 neutrons per second. Thus the difference between DREO measurement and source calibration was 3%, comparable to the initial calibration uncertainty of 3% and an estimated DREO uncertainty of 4%.

The evidence of a slight departure from purely Maxwellian shape below 2 MeV is also fully consistent with that previously observed using neutron time-of-flight spectroscopy [1].

Gamma-rays from Cf^{252} are less useful in terms of detector calibration since there is no simple spectral representation and the total emission rate depends partially on fission product buildup (and hence age) within the source. Secondary gamma-rays produced following neutron absorption within the source encapsulation and surrounding structures add also to the uncertainties. The unfolded gamma-ray spectrum obtained also during the measurement on 26 Oct 1981 and shown in Figure J-2, is nevertheless consistent with the results of other investigators.

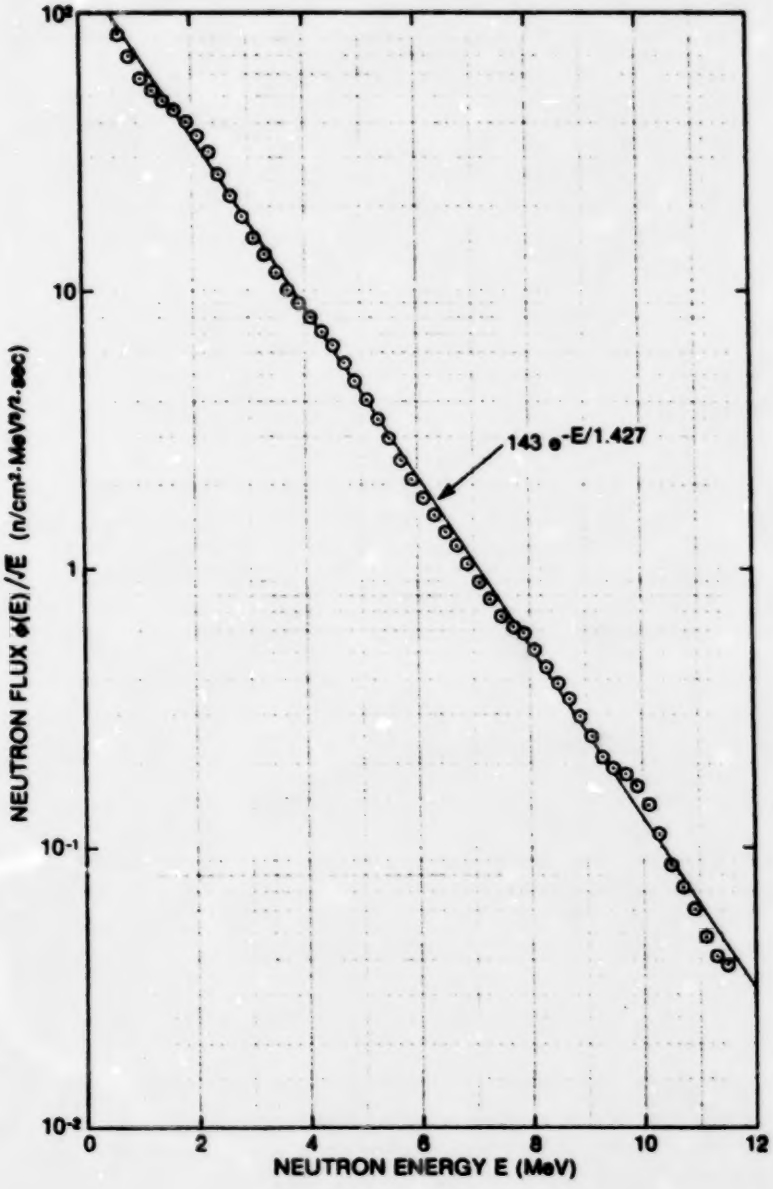

Figure J-1: Neutron Spectrum Recorded by DREO One Meter from the APRD Cf^{252} Source

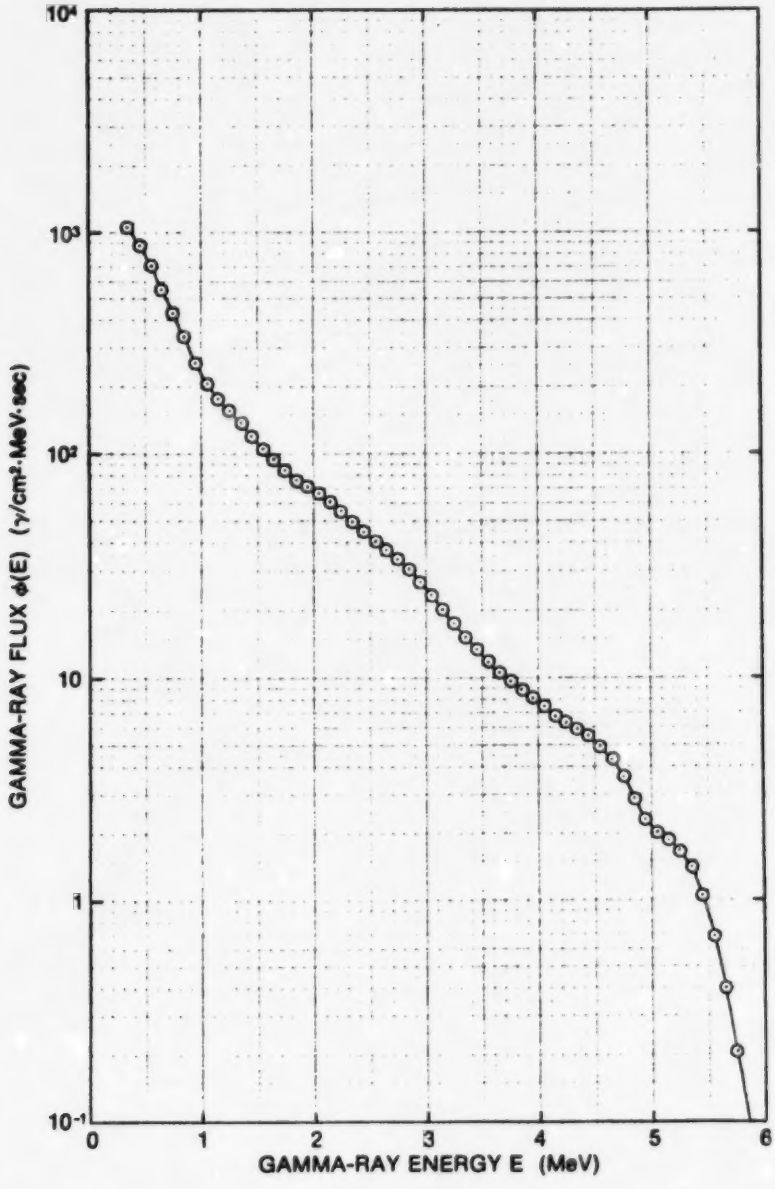

Figure J-2: Gamma-Ray Spectrum Recorded by DREO One Meter from the APRD Cf^{252} Source

Additional confirmation of the accuracy of DREO unfolding techniques is available from a previously unreported experiment at DREO during 1978. Spectroscopy using the same NE-213 scintillator system exposed to a borrowed two-milligram Californium-252 source [3] was performed at five source-to-detector separation distances, both with and without an intervening paraffin shadow bar. The neutron and gamma-ray spectra so determined were essentially identical to those presented previously (Figure J-3). Net neutron fluences so measured above thresholds of 600 keV are tabulated below:

DISTANCE (m)	FLUENCE ϕ ($n/cm^2.sec$)	$4\pi r^2\phi$ (n/sec)	DEAD TIME (%)
5	1048.	3.29×10^9	42
10	232.2	2.92×10^9	13
15	98.36	2.78×10^9	6
20	52.85	2.66×10^9	3
25	31.49	2.47×10^9	2

Extrapolation of these $4\pi r^2$ fluences to the source point by least-squares indicated a source strength above 600 keV of 3.27×10^9 neutrons per second and an atmospheric relaxation distance of 91.5 meters, as shown in Figure J-4. Note that the 5 meter point had been excluded from the fit due to excessive dead-time (42%). The fitted coefficient of correlation was 0.986 indicating the assumption of exponential atmospheric attenuation was valid.

This source had previously been calibrated at the Savannah River Laboratory [4] on 11 Oct 1977 to have a total neutron emission rate of 4.62×10^9 (±3%) neutrons per second. The date of DREO measurement was 26 June 1978 consequently 257 days intervened from the SRL calibration, thus reducing the expected source strength to 3.84×10^9 neutrons per second (assuming a 966.5 day half-life). At DREO the source was retained in position within a small aluminum cylinder of 1/8" walls, through which was ascribed a transmission probability of 0.985, resulting in a further reduction to 3.78×10^9 neutrons per second. Assuming the spectral shape was well represented by:

$$\phi(E) = C\, E^{\frac{1}{2}}\, e^{-E/kT}$$

where kT was measured at DREO to equal 1.44 MeV, integration above 600 KeV indicated that 87.9% of the emitted neutrons would be detectable above the NE-213 lower threshold. The expected effective source strength was therefore 3.32×10^9 neutrons per second, comparing favourably to the DREO-measured value of 3.27×10^9 neutrons per second, the difference of 1.5% falling within estimated SRL calibration error (3%).

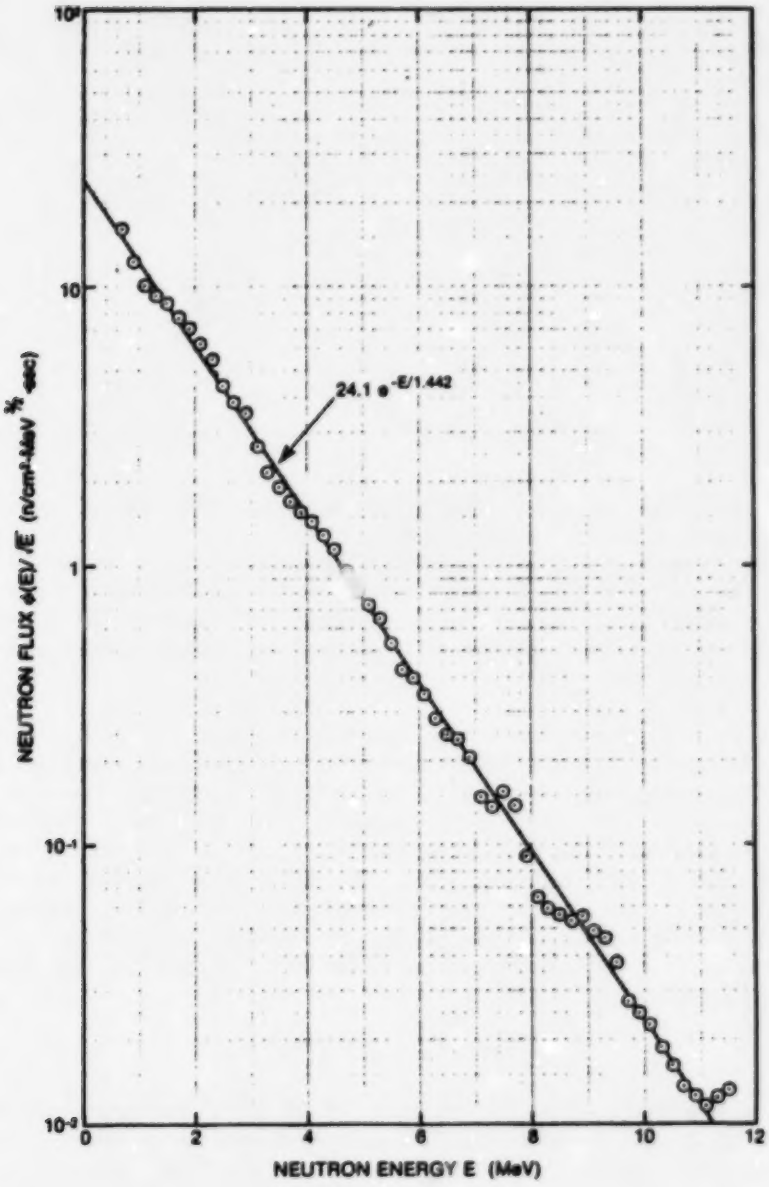

Figure J-3: Cf^{252} Neutron Spectrum Recorded by DREO in 1978

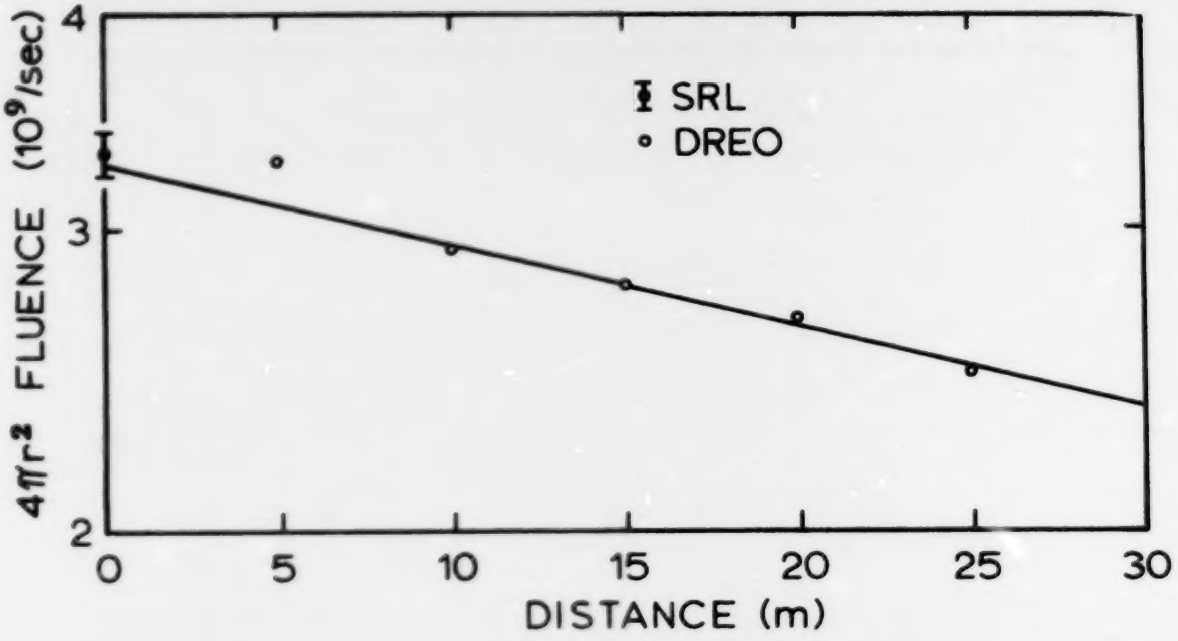

Figure J-4: Comparison of DREO Measurement to SRL Calibration of the Neutron Emission Rate (> 600 keV) from a Californium-252 Source

References to Appendix J

[1] L. Green, J.A. Mitchell and N.M. Steen, "The Californium-252 Fission Neutron Spectrum from 0.5 to 13 MeV", Nuclear Science and Engineering, 50, 257-272, (1973).

[2] H.A. Robitaille, and B.E. Hoffarth, "A Comparison of Measured and Calculated Air-Transported Radiation from a Fast Unshielded Nuclear Reactor", Defence Research Establishment Ottawa, DREO Report No. 835, (1980).

[3] L.G.I. Bennet, "Evaluation of Transportable Neutron Radiography", Royal Military College of Canada, (Aug. 1979).

[4] J.M. Boswell, "252-Californium Source Calibration; Source Identification Number CR-Cf-318c", Savannah River Laboratory, (20 Oct. 1977).

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13 ABSTRACT

Previously reported measurements of long-range air-transported neutron and gamma-ray spectra from the fast-critical facility at the US Army Aberdeen Proving Ground have been supplemented recently at the 1080-meter position. The results of these determinations are presented herein and compared to several recent calculations from other research establishments.

In addition, a summary of all dosimetric measurements obtained in the period 1979-1982 are appended, as are new determinations of APRD soil composition.

Integral quantities such as neutron and gamma-ray kermas are very well predicted by the latest calculations, however there still exist significant spectral differences. At short ranges calculated neutron spectra are somewhat softer than experimental measurements, but at the farthest range of 1080 meters agreement is suprisingly good. Gamma-ray spectra remain well-calculated at all ranges.

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